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# WALL EFFECTS IN WIND TUNNELS

J.P.. Chevallier and X. Vaucheret



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16. Abstract

A synthesis of current trends in the reduction and computation of wall effects is presented. Some of the points discussed include: (1) for the two-dimensional, transonic tests, various control techniques of boundary conditions are used with adaptive walls offering high precision in determining reference conditions and residual corrections. A reduction in the boundary layer effects of the lateral walls is obtained at T2; (2) for the three-dimensional tests, the methods for the reduction of wall effects are still seldom applied due to a lesser need and to their complexity: (3) the supports holding the model of the probes have to be taken into account in the estimation of perturbatory effects.

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WALL EFFECTS IN WIND TUNNELS

by J.P. Chevallier and X. Vaucheret

## INTRODUCTION /3*

The recent first commercial operation of the NRF high Reynolds number wind tunnel (NASA Langley) [1] , the European ETW wind tunnel project [2] and the continuous request of manufacturers for more specific test conditions in existing installations have led to the creation of different work groups to study the problem of wall effects from the three-fold standpoint of their determination, their reduction and their correction. We may mention in particular an AGARD work group under the auspices of the "Wind Tunnel Testing Subcommittee of the Fluid Dynamics Panel" [3], and the GARTEUR action groups [4]. The most important results were also presented during the following meetings:

-AGARD-FDP Meeting at London on May 19, 20, 1982 (17 reports on wall effects in wind tunnels) [5];

-AGARD FMP Meeting at Smyrne on October 11 to 15, 1982 [6];

-Working sessions on "the reduction and correction of wind tunnel wall effects" NASA Langley Research Center January 25-26 1983 [7].

-53rd AGARD FDP Meeting on "Wind Tunnels and Testing Techniques" at Cesme on September 26 to 29, 1983 where 36 reports were presented, particularly that of Bionion and Kraft [8], presenting the conclusions of the 1982 meeting at London [5].

Of all studies presented, our purpose is to reveal which of these are current trends and to specify our own practices. To accomplish this, we shall first examine the means currently used to reduce wall effects, then recent methods of calculating these effects, because the two problems are now intricately interrelated.

It seems that there is a quasi general agreement on the need to use measurements of the speed field in the vicinity of the walls to calculate interferences. Measurements of the same type will be used for testing the boundary conditions when we try to minimize these interferences.

In the second part the methods are applied to industrial wind tunnels based on parietal measurements so as to test the representation of the model and its support.

## 1 - VARIOUS METHODS FOR REDUCING OR CALCULATING WALL EFFECTS

### 1.1 - REDUCING WALL EFFECTS

It is generally achieved because the term "adaptive walls" is used. It is a vague term covering highly diverse practices using for example:

-permeable walls (perforated walls with variable porosity, fractionated suction chambers, controlled back-pressure; changing slits with valves or counterplates; transversal flaps),

-flexible solid walls. /4

Various devices for measuring the speed field are combined with these means of testing the transversal flow component: isolated probes, longitudinal tubes fitted with pressure taps, laser velocimetry, parietal taps. We will limit ourselves to a brief description of operational systems, the results of which are published and to the most advanced projects, primarily for two-dimensional testing. The characteristics reduced in terms of test section height (table 1) facilitate comparisions.

-Wind Tunels With Perforated Walls and Multiple Chambers

The first developed at CALSPAN based on Sears' ideas [9] has a section 25 cm wide and 30 cm high, walls with normal perforations (22.5% opening) with 8 lower chambers and 10 upper chambers, tested individually. Measurements of the flow speed and direction on the control surface, performed at the beginning with clinometric probes now are due to the calibration of longitudinal tubes equipped with 2 rows of pressure taps arranged over opposite generators. These tubes, installed over a rotary support, should enable measurements to be performed on a cylindrical control surface for the extension of three-dimensional flows (Wind tunnels 1T, then 4T of AEDC) figure 1.

-Wind Tunnel With Slits and Multiple Chambers

At the center of AMES [10], a 25 x 13 $cm^2$ wind tunnel has 6 suction compartments for each wall. These compartments are in turn divided widthwise into 3 chambers for a three-dimensional adaptation. The measurement of 2 disturbance speed components on one control surface is replaced by the use of 2 control surfaces with measurement of the one cross-component using a laser velocimeter.

-2D Wind Tunnels With Solid Flexible Walls

At the Univeristy of Southampton, the TSWT (Transonic Self Streamlining Wind Tunnel) has a 15 x 15 $cm^2$ square section and a very long test section (1.12 m) whose upper and lower walls are each shaped using 20 electric actuators with a similar number of parietal pressure taps [11]. As such the wind tunnel was used for two- and three-dimensional testing to determine whether the disturbances to be measured on the walls of these are difficult to obtain with precision (figure 1).

At the Technical University of Berlin [12], the T.U.B. wind tunnel has a 15 x 15 $cm^2$ square section with two flexible walls over 0.69 m each shaped by 8 direct current acutators with a 25 mm path and equipped with some 20 pressure taps.

At CERT at Toulouse, the T2 wind tunnel [18], which was the subject of 2 reports [13, 14] has over its competitors the advantages of one order of magnitude at least with respect to the Reynolds numbers (0.37 x 0.38 $m^2$ test section and generating pressure 5b) and an excellent relative precision in the knowledge of wall shapes (using potentiometers of about 0.05 mm) and speed distributions (with 91 pressure taps on each wall). By vectorizing the program for calculating the virtual field and optimizing the relaxation factors reducing the time required for adaptation during a gust of a few tens of seconds.

In addition to these advantages, the T2 wind tunnel has a rela- /5
tively short test section (table 1). What can we conclude about the precision of the reference conditions obtained in these conditions? We shall return to this essential point after a brief review of the new methods of assessing wall effects. It should be pointed out that an attempt has been made to compensate for lateral boundary layer effects using reliefs made by gluing paper cut out in the shape of level lines [15]. This procedure finds its justification in recent CEAT tests [16] which show the existence at the root of the model two small counter-rotative vortices, very different from the modelization proposed by Preston [17].

### 3D Wind Tunnels With Flexible Walls

At the NASA center of Wright Field a 9' x 9' test section (i.e. about 23 x 23 cm) operating under 4b has 2 flat side walls whereas the other two are made up of flexible rods with alternating circular and triangular sections activated by some 100 actuators. No measurement was performed on the walls [3].

At the Technical University of Berlin [12] a second test section, with an 18 x 15 $cm^2$ octogonal section, is used for 3D tests. The feasibility of such tests was demonstrated recently in an operation at Cesme in September 1983 (figure 3), despite the small deformations to be achieved (of the order of one mm).

At DFVLR, in the advanced project, Dehnbare Adapative Meb-strecke (DAM) the circular test section was made up of an elastic tube 800 mm thick whose diameter was stretched into 8 sections by 8 actuators [12] (figure 5).

## 1.2 - NEW METHODS OF CORRECTING WALL EFFECTS

This was the title, in singular form, of a report presented at the 14th Symposium of Applied Aerodynamics at Toulouse in 1977 [19]. We still use this name for methods which have multiplied for 6 years and whose common points is to call on measurements made on walls or in their vicinity. Created from the necessity of being applicable to adaptive, but not perfectly adapted walls, this type of method has for conventional walls the advantage of eliminating certain controversial assumptions on lineary boundary conditions [18, 20].

Without going into too much detail, we may mention the following methods in the order they appeared:

Kemp: the unknown intensity of the singularities arranged at the walls and at the location of the model is determined to satisfy with speed measurements on an equal number of control points, on the model and at the walls, by resolving the linear system formed with the corresponding impact factors. The parietal singularities thus defined contribute alone to the interferences under investigation.

-Smith [25]: the NLR I method differs from that of Kemp only in the limitation of the unknown singularities at the wall, the model being represented by given singularities, functions of its geometry and of overall lift and drag measurements.

Capalier et alii [19]: in contrast to the two aforementioned methods the formulation expressed in terms of integrals of the speed deviations measured at the walls and calculated for the model avoids resolving the linear system and therefore eliminates the consequences of random errors in the measurements. This method applies not only to the two-dimensional case, but also to three-dimensional flows in test sections with a rectangular section and flat side walls.

Swada [22] presented a very similar method which he recently applied to two-dimensional unsteady flows [37].

Mokry and Ohman [23]: Direchlet's problem for the axial speed inside the surface upon which boundary data are collected is solved in the form of a Fourier-Bessle series for three-dimensional cases. Their coefficients are obtained using rapid Fourier transforms.

For corrections calculated on the axis of the test section, a cylindrical control surface may be used no matter what the shape of the test section has.

Mokry compared these methods [24] on a two-dimensional test case and showed that [19] and [23] gave identical results and [22] and [25] deviated only very slightly.

Ashill [27] as well as Smith in the unpublished NLR II method avoiding the use of the model which may be delicate in the presence of supersonic or separation regions in the flow. They should therefore use measurements of the two disturbance components in the vicinity of the walls.

All of these methods are of the linear type and are limited for this reason below M = 1. Also they implicitly assume that the boundary conditions are homogeneous enough for the measurements near the walls to be significant.

For any method used, the precision required in knowing the two disturbance components will be brought to light through the explicit formulation of the speed and incidence corrections based on the relative longitudinal disturbance component *u* [19] cu, according to the so-called conjugated formulation [28] on the relative transversal component . By letting *ui* and *vi* be the wall interference components at the center of the test section and by simplifying the formulas given in [18] based on an empty test section.

$$(1)\quad u_i(x,0) = \frac{1}{\beta h}\int_{-\infty}^{\infty} \frac{u(\xi, h/2) + u(\xi, -h/2)}{2\,\mathrm{Ch}\,\pi(\xi - x)/\beta h}\, d\xi$$

$$(2)\quad v_i(x,0) = \frac{1}{h}\int_{-\infty}^{\infty} \frac{u(\xi, h/2) - u(\xi, -h/2)}{e^{2\pi(\xi - x)/\beta h} + 1}\, d\xi + C$$

$$(3)\quad u_i(x,0) = \frac{1}{h}\int_{-\infty}^{\infty} \frac{v(\xi, h/2) - v(\xi, -h/2)}{e^{2\pi(\xi - x)/\beta h} + 1}\, d\xi + C'$$

$$(4)\quad v_i(x,0) = \frac{1}{\beta h}\int_{-\infty}^{\infty} \frac{v(\xi, h/2) + v(\xi, -h/2)}{2\,\mathrm{Ch}\,\pi(\xi - x)/\beta h}\, d\xi$$

No problem is raised by using formula (1) because it was shown that it tolerates the truncation of the integration terminals owing to the rapid decrease in the impact function and the fact that it eliminates the reference errors. The same is true for formula (4) in regard to incidence. Conversely, for formula (2) it is necessary to determine the constant C. It is zero if we adopt as reference a flow direction which is sufficiently upstream so that the difference $u(\xi, h/2) - u(\xi, -h/2)$ is zero. It also shows in the nucleus of the integral a speed difference which is delicate to measure.

Based on these formulas we therefore conclude that to apply the so-called new correction methods it is necessary to know, at a right angle with the model, the speed vector in modulus and direction, in the vicinity of the walls, with a precision of the same order of as that required on so-called "upstream infinity" conditions.

## 1.3 - DETERMINING THE REFERENCE CONDITIONS

The crucial importance of determining these conditions accurately was recently recalled in a report under the "Wind Tunnel Testing Techniques" Committee of AGARD-FDP which set fort the requirements of airplane manufacturers with respect to wind tunnels [29].

The investigation of an error limited to $\Delta C_X = 0.0001$ leads to $\Delta M = 0.001$ and $\Delta\alpha = 0.01°$ in regard to the Mach number and the incidence. This goal, which seems a challenge, actually deserves considerable effort because in other sources [30] it is shown that a 1% gain in the cruise drag (considerable only in these conditions) is profitable even if we have to quintuple the number of aerodynamic tests of a transport aircraft.

How can we possibly know the direction and speed of an "infinite upstream" flow in a wind tunnel with such accuracy?

Excluding the support effects, which will be discussed in the second part, and remembering that we have to know the direction and speed on a control surface with the same precision, by examining the errors inherent to the various procedures for measring the flow disturbance components (laser, clinometric probes, etc), here at ONERA we think that there is only one valid procedure: using deformable solid walls where the quality of the surface condition and pressure taps is equal to that obtained on airfoils and position measurements showing the shape of the wall (which will be corrected for the boundary layer displacement thicknesses).

Among the wind tunnels which try to achieve these conditions, we see that T2 has a shorter test section, but that it is long enough to define the reference conditions perfectly, given the balance functions discussed above. It has the largest number of parietal pressure measurements and actuators near the model and the best definition of the wall positions. The scope of the displacements is slightly smaller and as a result the dimension of the model is limited. The displacement pitch in other regions is too strong.

In these apparently optimal conditions, has the objective focussed on been achieved? It is virtually impossible to calculate an error: the shapes of adaptive walls are derived by processing an external virtual flow using Green's formula and whose parietal speed measurements are the data. Conversely, the overspeeds at a right angle with the model are also functionals of /8
the slopes obtained by smoothing and interpolation of the measured dimensions. An intrinsic validation was therefore tried by placing the same mdoel (CAS 7 airfoil with a 200 mm chord) over the axis of the wind tunnel and at 80 mm below this axis. By adapting each case, the wall shapes and parietal pressure distributions are totally different [15]. The variation of the lift factor as a function of the Mach number for angles of 0 and 1°, shown in figure 6 on a large scale, shows the dispersion of the measuring points. The latter does not show any systematic deviation due to the difference in testing conditions and it seems small enough for us to be able to conclude that the objective is virtually if not fully achieved. This success in two-dimensional testing leaves promising prospects for extensions to three-dimensional flows provided that all precautions are taken to observe the purety of the flows, the homogeneity of the boundary conditions and the precision of the parietal measurements in the presence of considerably smaller disturbance fields.

## 2 - WALL AND SUPPORT EFFECTS IN ONERA'S INDUSTRIAL WIND TUNNELS

In wind tunnels not yet equipped with adaptive walls and with magnetic suspensions, it is still necessary to make corrections for wall and support effects to restore as far as possible the results which would be obtained on models in an unlimited atmosphere. There are two types of corrections to be made for the potentials under consideration:

-the wall effects are calculated based on the interference potential promoted by the walls,

-the support effects are the result of the sum of the potential of the supports in an unlimited atmosphere and of the interference potential promoted by the walls.

### 2.1 WALL EFFECTS

Two methods are currently employed for calculating wall effects. These methods have already been presented.

The first method, called the "<u>conventional method</u>" [31] consists of calculating the potential promoted by the walls by solving a problem whose data are the following:

-the potential of the model in an unlimited atmosphere,

-the boundary conditions on the walls of the test section involving the concept of equivalent uniform wall porosity.

The second method, called the "signature method" [19] allows the potential promoted by the walls to be derived from data consisting of:

-the potential of the model in an unlimited atmosphere,

-the distributions of pressures measured on the control surfaces of the test section (signatures).

These two methods have in common the assumption of a cylindrical test section reaching to infinity, and the necessity of making use of a mathematical description of the model. /9

## 2.1.1 Mathematical Description of the Model

Since we are referring to a corrective calculation and not a calculation of the flow on the model, the specification of the model is rudimentary: it should include the required number of singularities for the model field to be properly represented at a distance from the model. The best way to control the specification consists of comparing the signatures measured and calculated on the walls of the test section in a configuration with perfectly known boundary conditions: in this case the use of solid walls is unambiguous.

The iterative process (figure 7) is the following: using signature measurements on the walls of a guided test section, in the presence and in the absence of a model, by adding and subtracting we find the parts for the locking and lift terms corresponding to an isolated model. The model specification associated with zero porosity conditions of the walls makes it possible to obtain signatures at the same locations of the test section and to divide them into locking and lift terms. An examination of the differences between calculated and measured signatures makes it possible to check whether the model specification should be improved and in this case which part of the specification, volume, wake, lift is to be altered to be acceptable in terms of manufacturer specifications.

Two examples illustrate the mathematical specifications of the model.

The first example concerns tests on a profile in a flat current in S3MA in a guided test section configuration. An example of the signatures measured in the presence of a profile, then corrected of the readings in the absence of a profile (figure 8) show that the tapping errors were eliminated as well as the effect of the wake comb located downstream. A comparison of the calculated and measured signatures (figure 9) show that the lift description due to two intensity vortices derived from measurements of $C_Z$ and $C_M$ is adequate [32]. At zero lift, the description of the volume using a single doublets is also adequate. Conversely, the description of the wake using a single source is increasingly incorrect when $Z_Z$ (therefore $C_X$) increases. This is due to the absence of the tapping by considering the separations in the description. Work is now underway to correct this.

The second example concerns a space model (figure 10) in a 47 $m^2$ SIMA test section. The description of the streamlined bodies is here a double doublets number of the ratio between the length and diameter of the body. We see that the calculated signatures, in good agreement with the measurements, personalize well the shape of the model: flat signature for the fuselage alone, bulging for the entire spacecraft.

When the mathematical description of the model is considered to be correct, calculations may begin to correct the wall effects.

2.1.2 Signatures Method /10

As indicated above, this method does not require knowledge of wall porosities. One simply needs to measure the signatures over a control surface so that the wall porosity effects are homogeneous.

In perforated walls, and a fortiori solid ones, these control surfaces are the walls themselves. The duration of the signature measurements does not exceed that of the wake measurements of a flat current profile. This method is systematically applied to profile testing in S3MA. The corrected results obtained on the CAST 7 profile are in good agreement with those obtained in the test section with adaptive walls of the T2 wind tunnel of CERT/TOULOUSE (figure 11) as well as for the lift curves and for the stability curves of the maximum $C_Z$.

In the case of walls with slits, the signatures may no longer be sampled on the walls. According to a recent publication [20], the signatures should be recorded at a distance from the walls which is virtually equal to the slit pitch. This is a problem for the test section which as a limited number of slits.

### 2.1.3 Conventional Method

In addition to a correction description of the model, it is necessary in the conventional method to know the wall porosity laws as a function of the Mach and of the generating pressure and to validate the concept of uniform wall porosity.

The reference tests [31] are referred to determine the wall porosity laws. These tests may be obtained by performing tests on the same model, with the same Reynolds number:

-in the same test section rendered guided by the ventilation mask,

-in a test section with such dimensions that the wall effects are negligeable.

As far as possible the second type of reference is preferred because it has no limits due to the test section locking and does not require corrections which are high in three-dimensional cases.

The iterative process used for defining the porosity laws is the following (figure 12).

The work always includes an interpolation in M, $C_Z$ of the wind tunnel data. The first assessment of the deviations to be reabsorbed by corrections is established in incidence deviations as a function of $C_Z$ at a fixed Mach, and in $C_X$ deviations as a function of M for a given $C_Z$.

The deviations of M and $C_Z$ between interpolated results, corrected for the reference test and not corrected for the ventilated wall test are introduced into the curve networks established as a function of porosity. This gives the first porosity law. It is used to ocrrect the results of the ventilated wall test. The differences between the interpolated results corrected for both tests are then examined. If these differences satisfy the manufacturer's precision specifications, the work is completed. Otherwise, the process is repeated. In general, three iterations are necessary. If differences still exist, the reasons are investigated. /11

An examination of the pressure distributions measured on the walls of the test section make it possible to define the Mach-incidence limits beyond which the Mach number is greater than 1. In fact, this value is obtained on the ceiling and there is not yet any locking of the test section: the supersonic region on the top skin of the wings reaches the cieling. The wall corrections are no longer applicable. Figure 13 shows, for a corrected Mach, the limits obtained at SIMA for three slit conditions and at S2MA for 2 homothetic models.

In the case of an S2MA transonic test section, for two used conditions of perforated walls (by opening slide valves by 100 and 55% to modify the porosity), the porosity laws (figure 14) were established by using as reference tests tests on the same model in SIMA with an area 13 times larger than that of S2MA. These laws proved to be correct for full and half civilian aircraft models up to Mach 0.92 and for full military aircraft models up to the limits due to supersonic zones.

In the case of a 20 $m^2$ SIMA test section, the porosity laws (figure 14) of 4-slotted or 8-slotted open configurations were defined in the reference for tests performed in closed slotted configuration. These laws are correct up to Mach 0.85.

Beyond this value, there are still differences between the corrected results, obtained for the three test section cases, and an attempt is being made to resolve these differences.

2.1.4 Indirect Signatures Method

One variant of the conventional method consists of basing onself on the signatures calculation as a function of the porosity parameter assumed to be uniform and by comparison with the measured signatures to derive the wall porosity cartography. This variant was used for the case of the S3MA perforated wall test section. After verifying the correct description of the locking and lift terms in a guided test section, figure 15 shows that for perforated walls, a comparison of the signatures leads to a Q uniform porosity parameter Q of 0.2 on the walls. This porosity is moreover identical to that derived from the overall efforts in a guided reference test section.

In fact, this indirect signatures method is used to check the validity of the wall uniform porosity concept.

In test sections with perforated walls, a porosity test by comparing the measured and calculated signatures has not raised any special problems. As with this case the concept of a uniform equivalent porosity was not handicapped by examining the signatures. The conventional method was retained because it is not penalizing in terms of computer time, after the porosity laws are established. Generally speaking, the more the porosity concept is uniform, the more the mathematical description of models and stings proves to be inadequate. /12

## 2.2 MODEL SUPPORT INTERFERENCES

Corrections of the Mach number and of the Archimedean thrust brought about by the presence of model supports may be obtained experimentally based on measurements of the Kp distributions at the location which the model fuselage axis would occupy. A clinometric sounding would also make it possible to know the tail unit setting correction due to supports.

To avoid costly soundings, a calculation may be performed. Two methods are used at present.

The surface singularities method begins with a meshing of obstacles in the test section of on its walls. This technique is directly derived from techniques used by manufacturers in an unlimited atmosphere by adding the walls to simulate the contained atmosphere of the test sections. Illustrations of the meshing are therefore borrowed from manufacturers. Figure 16 shows [33] the sting and sting holder in the S5 guided test section of CEAT-TOULOUSE used by DASSAULT-BREGUET. Figure 17 shows the meshing of a Mirage model installed on the wall of the S2MA guided test section and of the device with 6 degrees of liberty to study load trajectories: calculations performed by LE BOXEZ of AMD-BA.

Figure 18 is concerned with the assembly of a civilian aircraft twin sting in a guided test section meshed by AEROSPATIALE. More complex cases including ventilated walls and descriptions of test section ends and upstream parts with tapered section are under study. This method is still complicated to use and requires powerful computers.

A description of test section obstacles using singularities distributed over their skeletons of various shapes has been tried recently by ONERA [34]. The only data are the coordinates of the assmbly skeleton and the area rule.

An attempt is made to validate this method in an unlimited atmosphere by comparison with the results of previous more sophisticated methods. Figure 19 shows, in these conditions, a good agreement of the Kps and incidence promoted by an inclined support used in a sabre assembly of the F4 model.

The support description is tested in the guided test section by comparing the measured and calculated signatures. In this case, a description of the model-support system is used. Figure /13 14 shows the case of an ONERA standard model assmbled in a sraight sting in the S3MA guided-rendered test section. A modelization with 20 doublets for the model and 15 for the sting provide a good agreement of the signatures.

Returning to the case of the F4 model in an S2MA transonic test section, figure 19 gives the Kp distributions on the line which the fuselage axis would occupy for various wall porosities.

We should insist on the relative magnitude of the wall effects and sting interferences. In the case of an S2MA wind tunnel (figure 20), in the perforated wall version with maximum rate, the incidence corrections are zero. The drag corrections resulting from the longitudinal gradients promoted on the support sting and the wall effects are in a 3 to 4 ratio for a civilian aircraft model. The sting interference is more crucial for military aircraft models whose incidences may exceed 40 degrees (and even higher for missiles) [35,36]. Given these high values and the stresses to contain, the volumes of model support mechanisms are such that the wall effects for a well conditioned test section may seem secondary. This real problem, in the absence of a magnetic suspension, deserves to be considered first for future active wall wind tunnels.

## 2.3 APPLICATION TO INDUSTRIAL TESTING

We now have correct descriptions of models and its supports and of the test section porosity laws. As of now the corrections are all calculated prior to testing for a specific case of a test section, wall configuration, supports, model.

These corrections (figure 21) include four parts:

-corrections relative to an empty test section obtained from corrected soundings, if necessary, and from the influence of the probe support,

-calculated or measured support interferences,

-corrections of wall effects and of the field impact of the model on the test reference.

In all the computer calculations provide a set of corrections depending on M, $C_X$, $C_Z$ (or incidence) expressed in the form of a table or polynomial laws which are introduced in the wind tunnel calculations to obtained real time corrected results. The correction calculations also provide the total field promoted by the walls and supports, for a Mach distribution and incidence correction on any point of the model. It is easy to know the spin and camber corrections of the wind promoted by the walls and the local M and tail unit setting corrections due to the model supports.

CONCLUSION /14

The advantage of pressure measurements on the walls of test sections was clearly established for calculations of wall effects. For reasons of convenience associated with the intended use of wind tunnels, these pressure measurements are still performed:

-occassionally in 3d to control the concept of uniform porosity of perforated walls and to check the mathematical descriptions of models and supports in a guided test section,

-systematically in 2D for direct access to corrections,

-imperatively in test sections with adaptive walls,

-finally with suspicion in test sections with slotted walls. The measurements should be performed at a distance from the walls which is technologically difficult to do.

If the advantage of additional measurements of the other component of the local flow on control surfaces is to eliminate any model description, a real problem of measurement precision has not yet been solved.

<u>Optimized test configurations</u> (test section, sting, model) is the result of a compromise between wind tunnel investments, the cost of testing and the quickness with which the results prepared are rectified. In three-dimensional cases, the wall effect levels are reduced by limitations in model size due to the span for civilian aircraft, due to the length for high incidence military aircraft. Small displacements of flexible walls will require greater accuracy in pressure measurements and in the positions of adaptive actuators. Test sections with 3d adaptive walls are still too recent to know their application limits and operating difficulties.

Meanwhile, it is suggested to use adaptations to the main point of a test program. These adaptations may concern:

-<u>models</u> whose manufacturing specifications account for distorsions in the flow of conventional walls (as practiced for aeroelasticity);

-<u>walls</u> which should meet specifications using conventional padding whether or not associated with improved ventilation distributions.

In any case, continuous revisions of concepts for minimizing wall effects should follow improvements in the specifications for precision required by manufacturers.

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Table 1

Wind Tunnels With Controlled 2D Boundary Conditions

| Wind Tunnel | Location | Test Section Section:(L×H) | Test Section Length/H | Boundary Conditions Control Nb Points | Boundary Conditions (paths, Threshold/H | Model C/H |
|---|---|---|---|---|---|---|
| T.S.W.T. | University of South Hampton | 15x15cm2 | 7.33 | 20 actuators | | 0.6 to 1 |
| T.U.B. | Technical University of Berlin | 15x15cm2 | 4.6 | 8 actuators | $\pm 0.16$ $5.10^{-4}$ | 0.66 |
| $T_2$ | ONERA-CERT Toulouse | 39x37 $cm^2$ | 3.5 | 16 actuators | 0.07 $10^{-4}$ | 0.3 to 0.5 |
| CALSPAN AEDC | Buffalo Tullahoma | 25x30$cm^2$ | 4.6 | 10 boxes (perforated walls) | Longitudinal Tubes 0.3° | 0.3 to 0.5 |
| NASA Ames | California | 25x13$cm^2$ | 5.66 | 3x6 boxes (slotted holes) | Laser Velocimetry over two 0.05° planes | 0.6 |

Table 2

Main Methods of Calculating Wall Effects Using Parietal Data

| Author | Data Required At Wall | Data Required On Model | Resolution Method | Applicability |
|---|---|---|---|---|
| KEMP [21] | $u_p$ | $u_m$ | n+p sing. distribution on wall and linear model system | 2D and potentially 3D |
| CAPELIER [19] | $u$ or $v$ | Cz,Ca,Cx geometry & measurement | Numerical Integration Explicity or tabulated Impact Functions | 2D and 3D in rectangular test section with flat lateral walls. |
| SMITH [25] NLR I | $u_p$ | Cz,Ca,Cx geometry & measurements | Singularities distributions on walls Linear system | 2D |
| SAWADA [22] [37] | $u$ | Representation of model | Fast FFT Fourier Series Green's theorem | 2D and 3D with unsteady 2D |
| MORRY [24] | $u$ | Representation of model | Fast FFT Fourier Series | 2D and 3D with cylindrical surface control |
| ASHILL [25] and NRL II | $u$ & $v$ | No representation | Green's theorem applied inside the control surface | 2D and 3D |

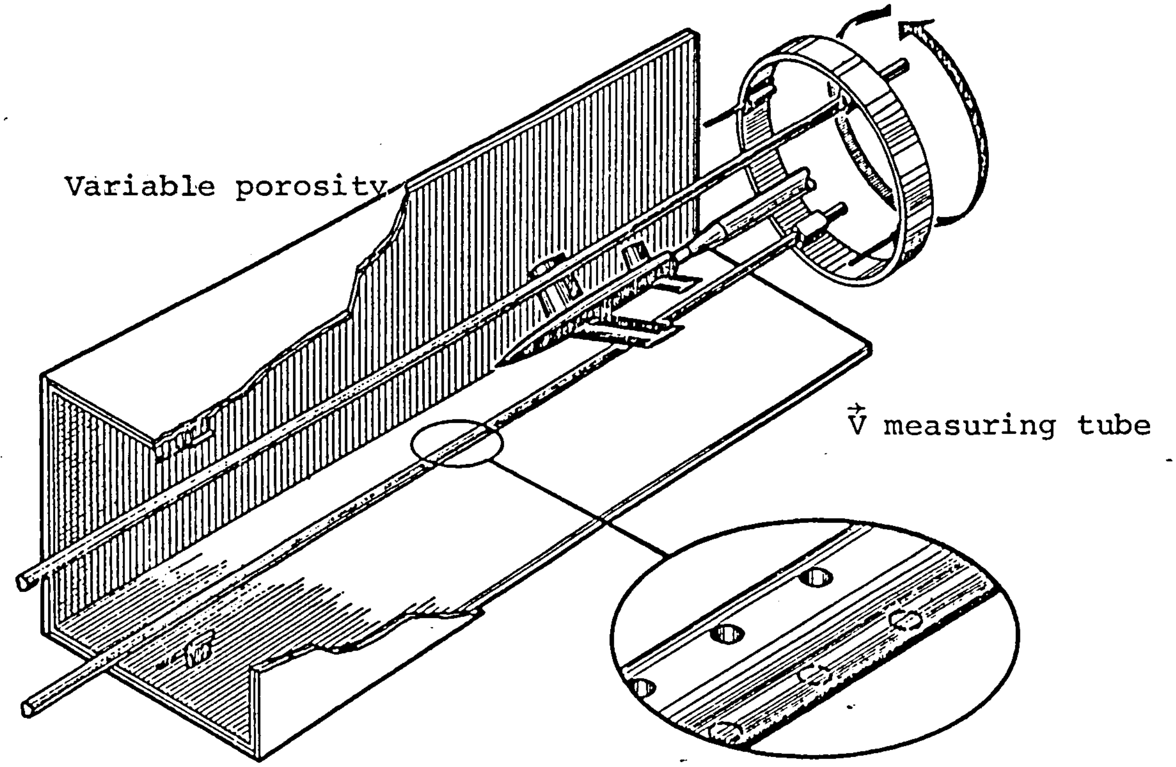



*Fig. 1 – A.E.D.C.*

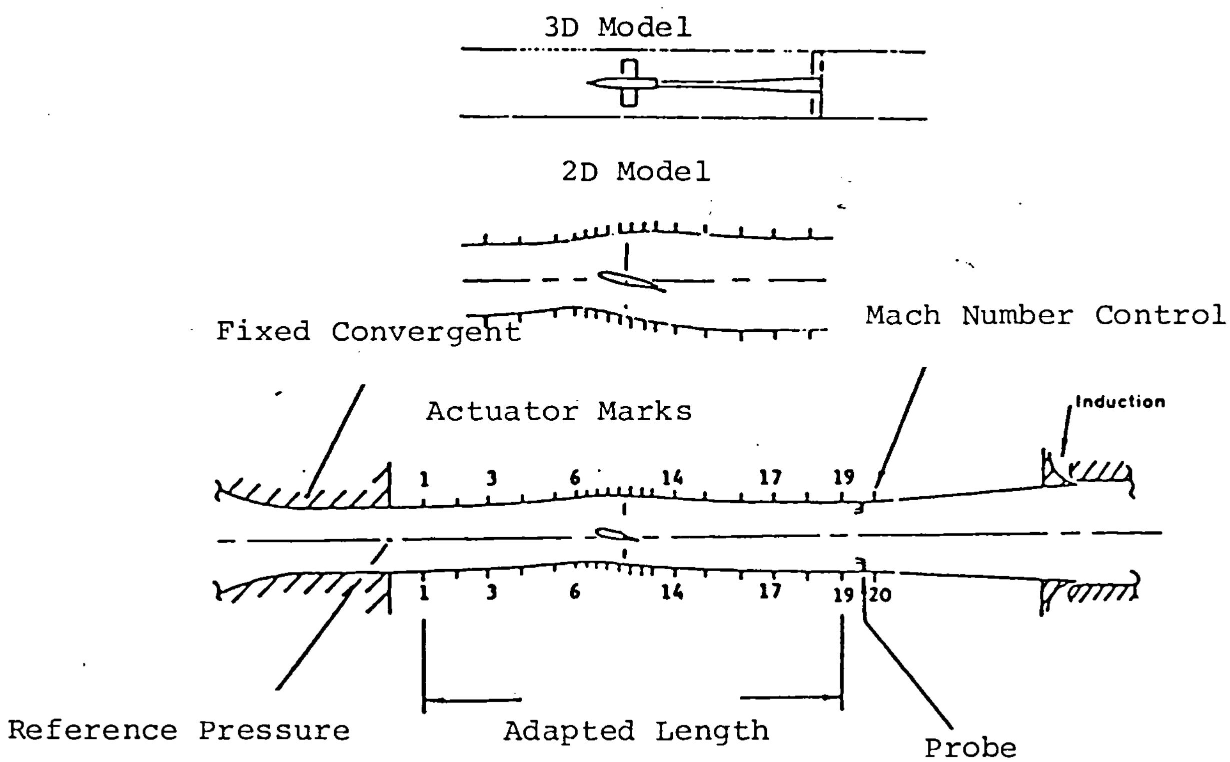



Fig. 2 - Wind Tunnel of Southampton University

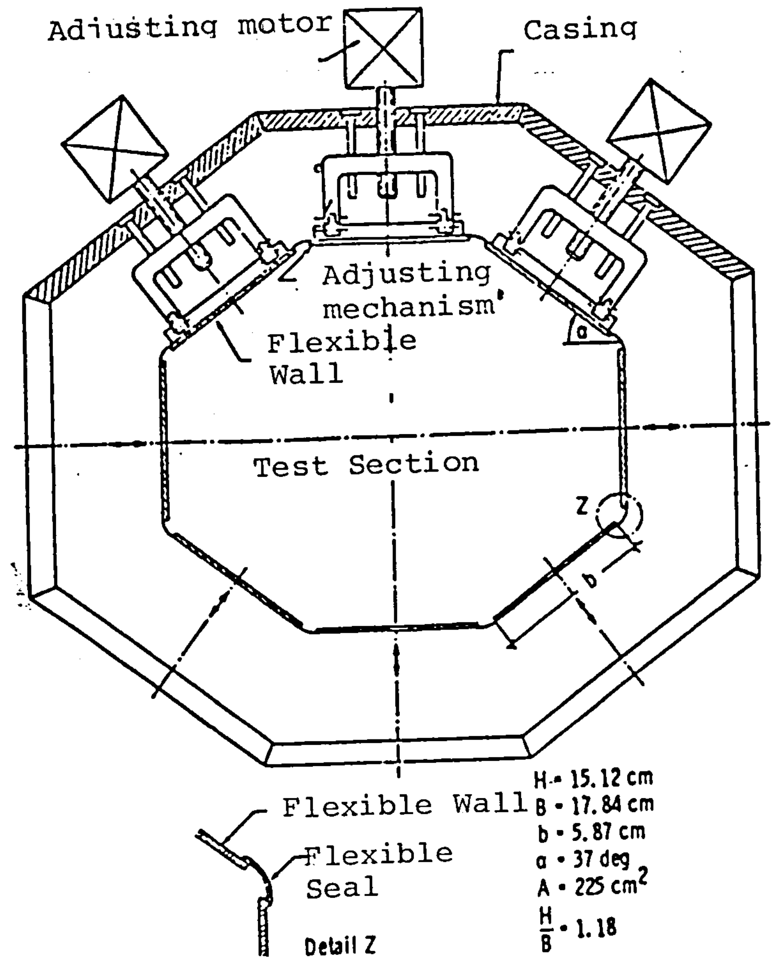



Fig. 3 - University of Berlin Wind Tunnel

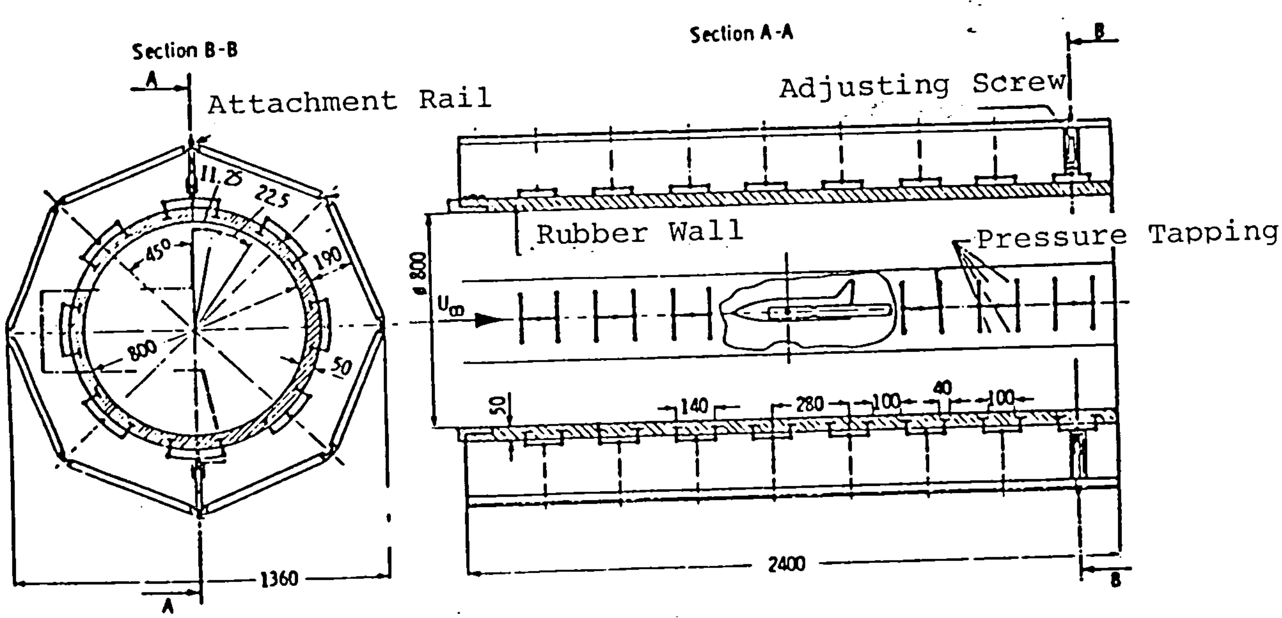



Fig. 4 - DFVLR Test Section Project with Elastic Wall

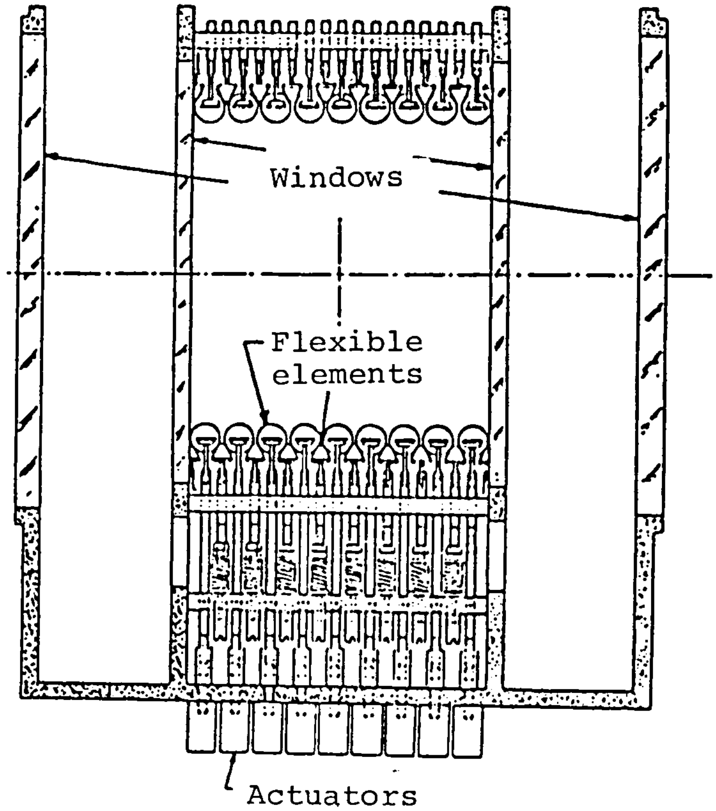



Fig. 5 - AFFDL Pilot Wind Tunnel With Flexible
Wall Elements

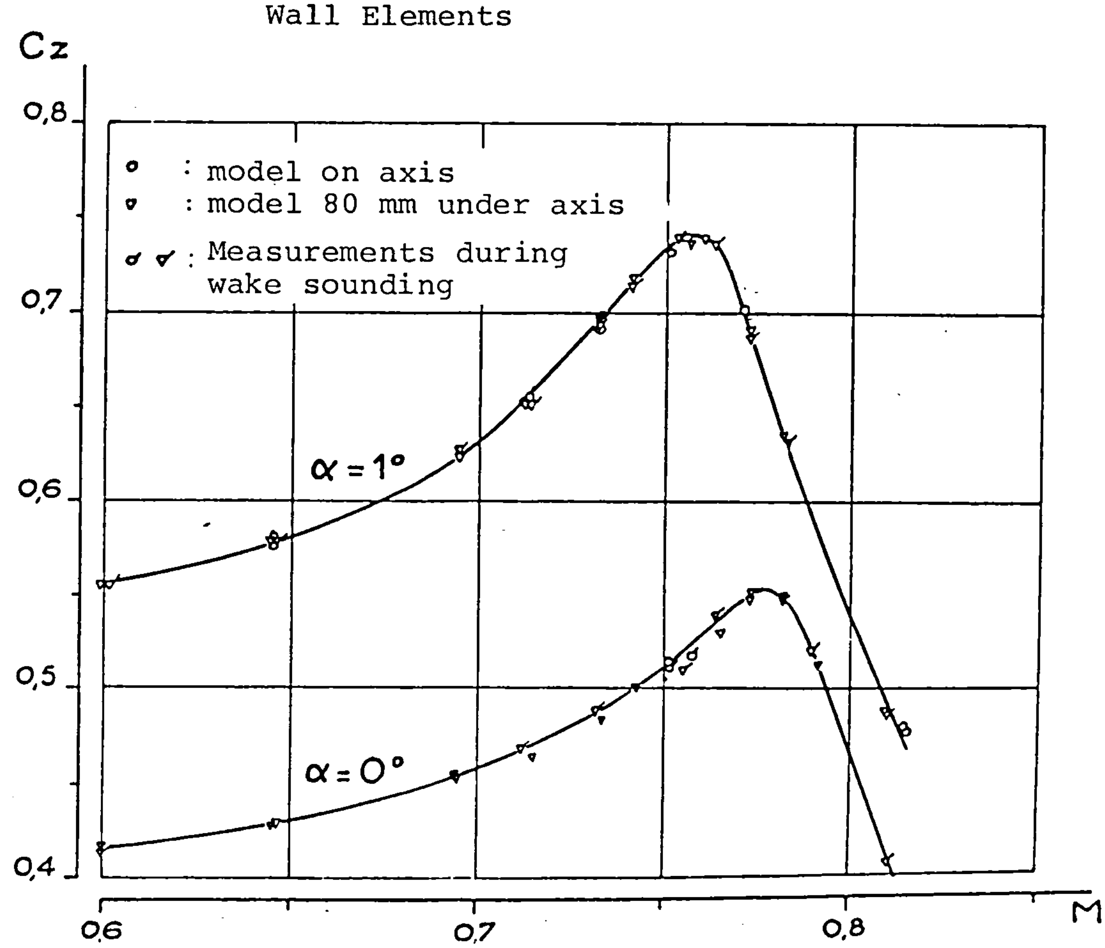



Fig. 6 - CAST 7 Profile. Lift as a Function of Mach Number

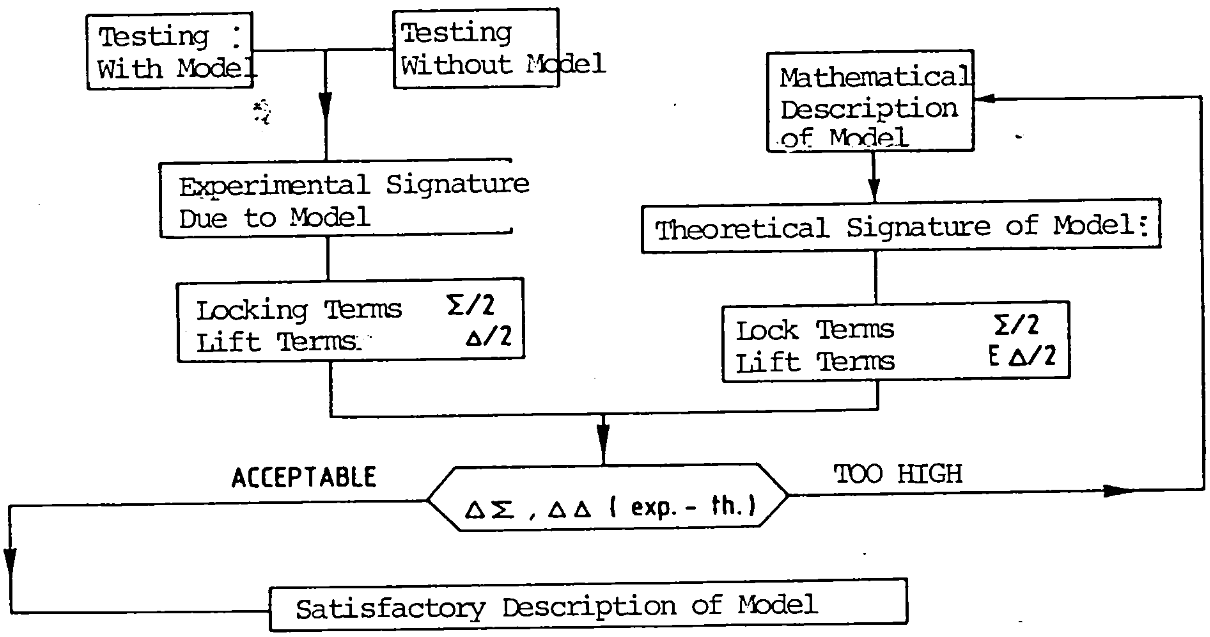
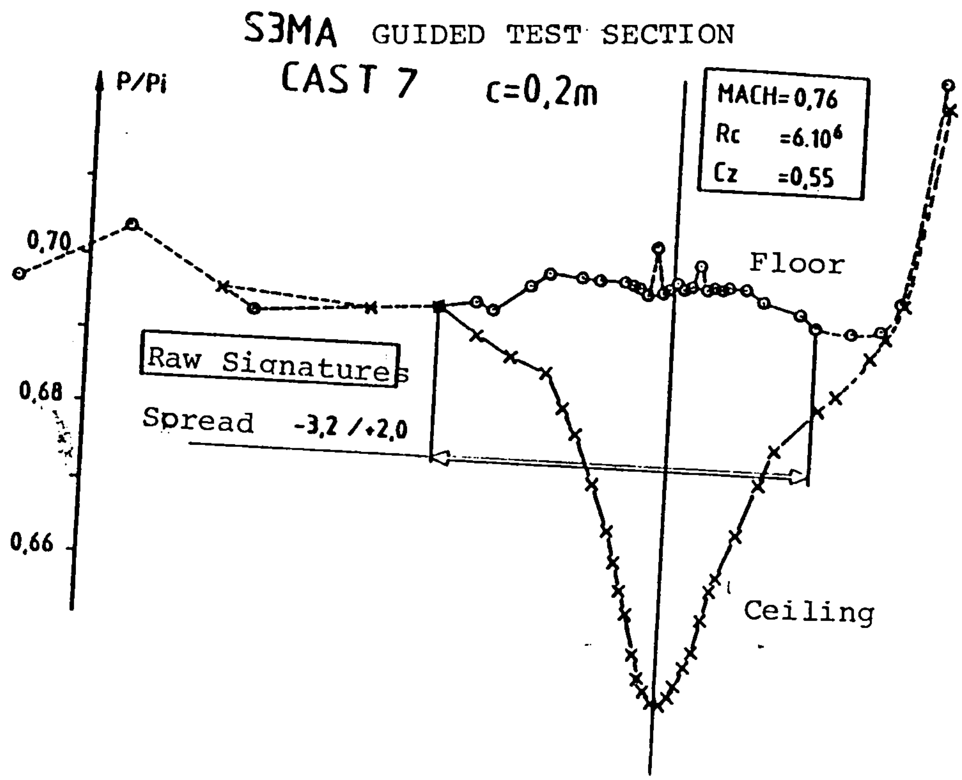



Fig. 7 - Description of Model in Test Section



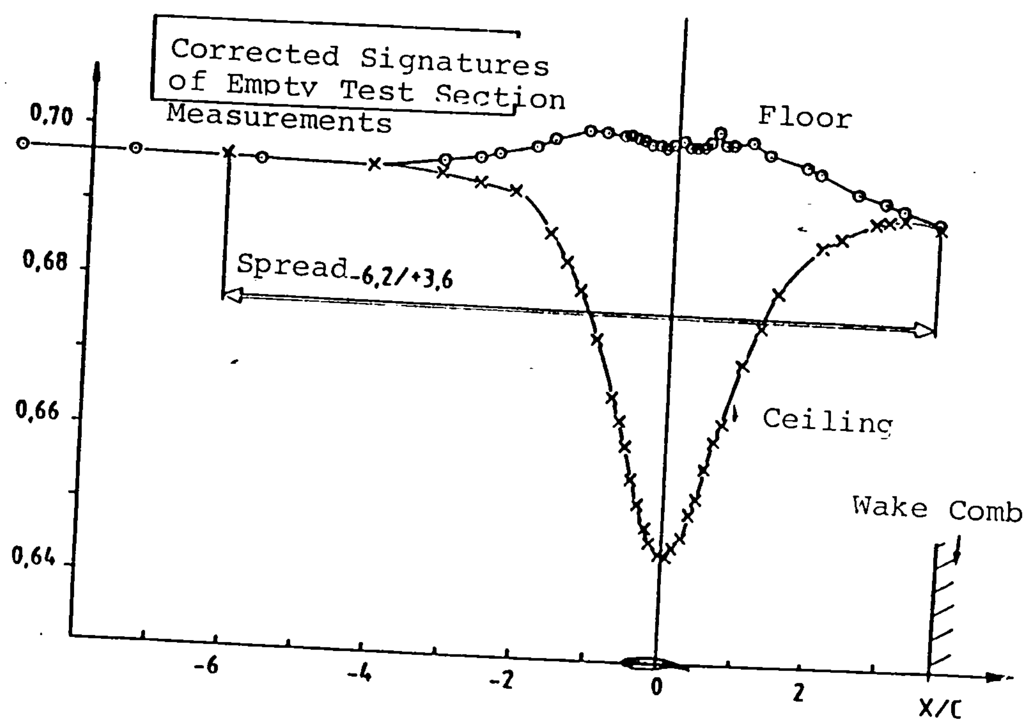




Fig. 8 - 2D - Rough and Corrected Signatures of Empty Test Section

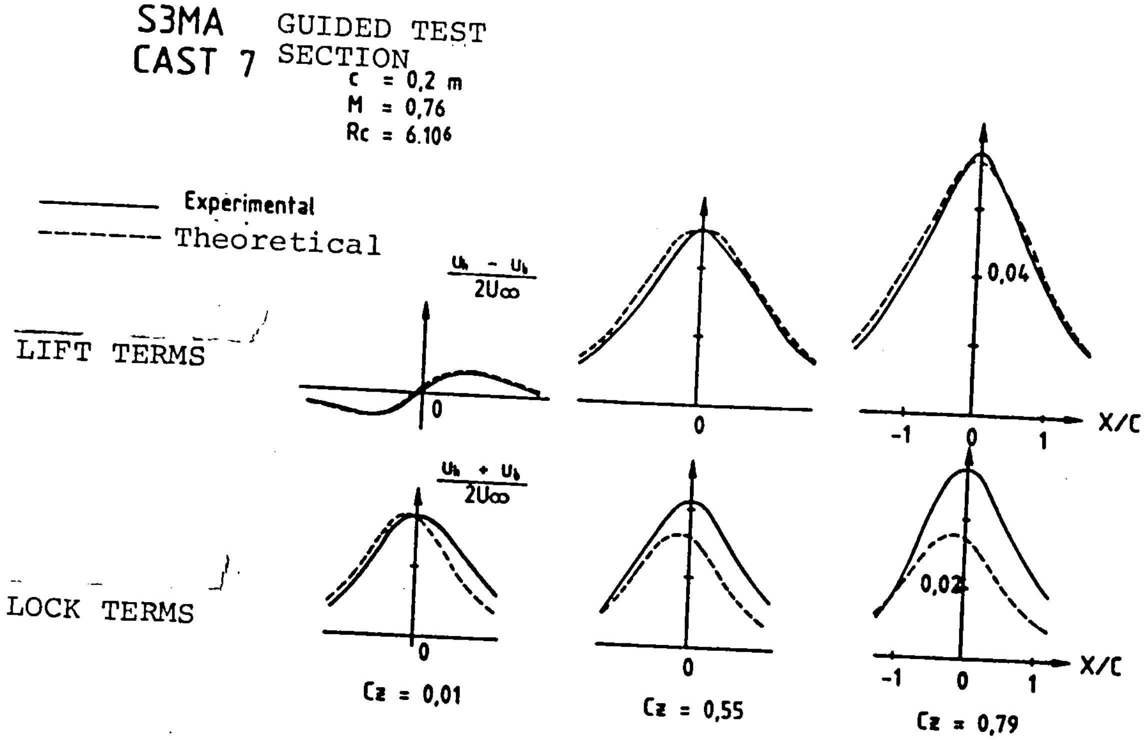



Fig. 9 - 2D Comparison of Calculated and Measured Signatures

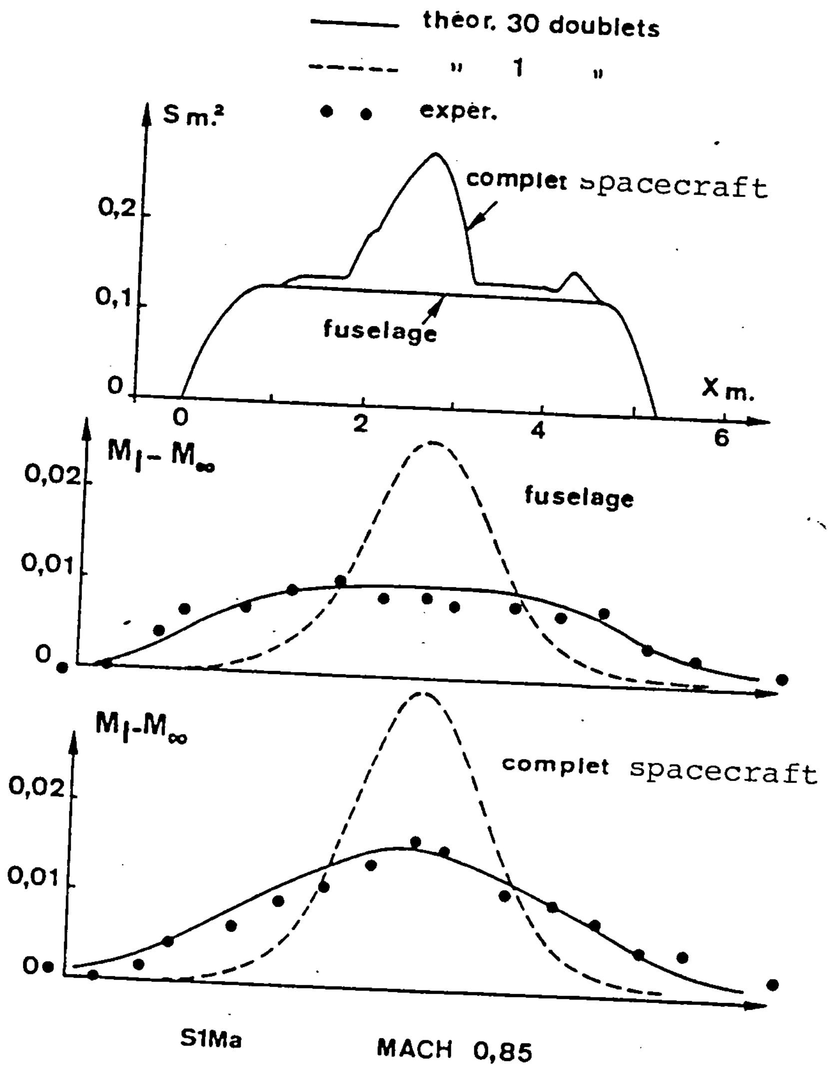



Fig. 10 - 3D Signatures on Solid Walls

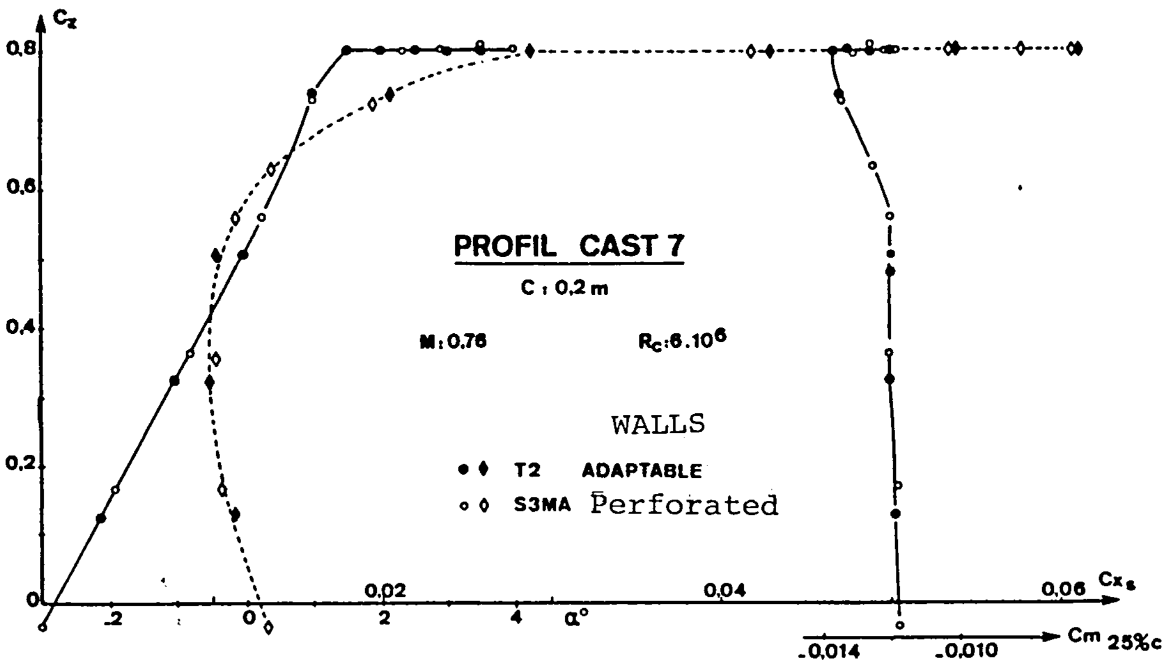



Fig. 11 - CAST 7 Profile - Comparison S3MA-T2 Results

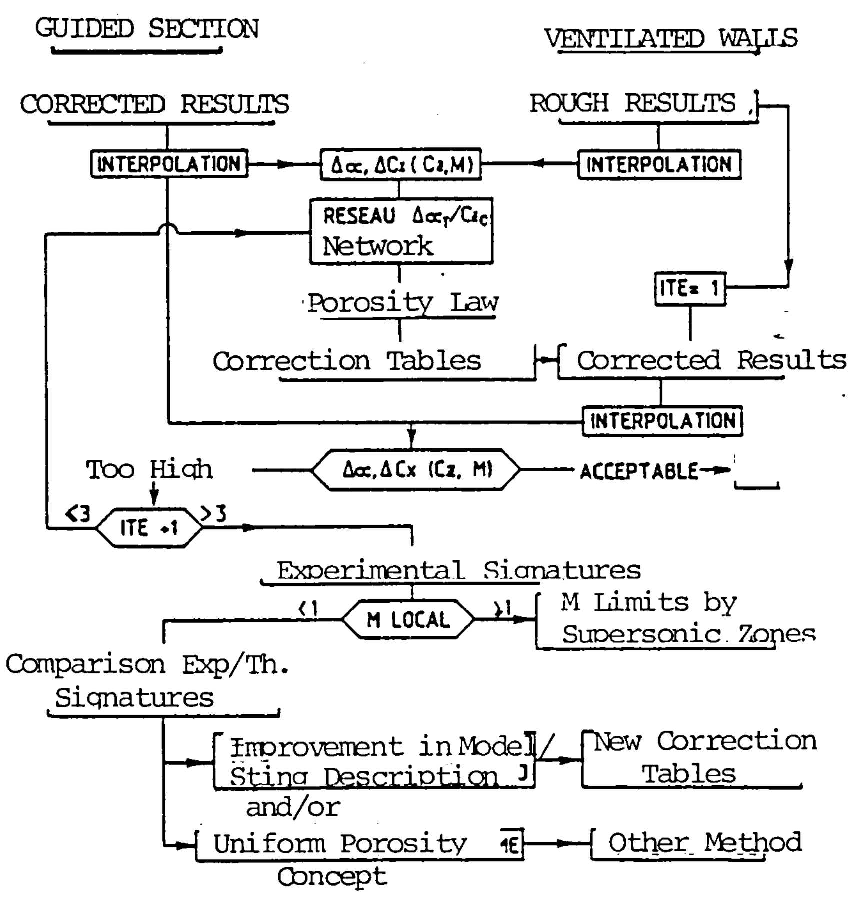



Fig. 12 - Determination of the Porosity Laws of a Test Section With Ventilated Walls.

M maxi / Walls = 0,1

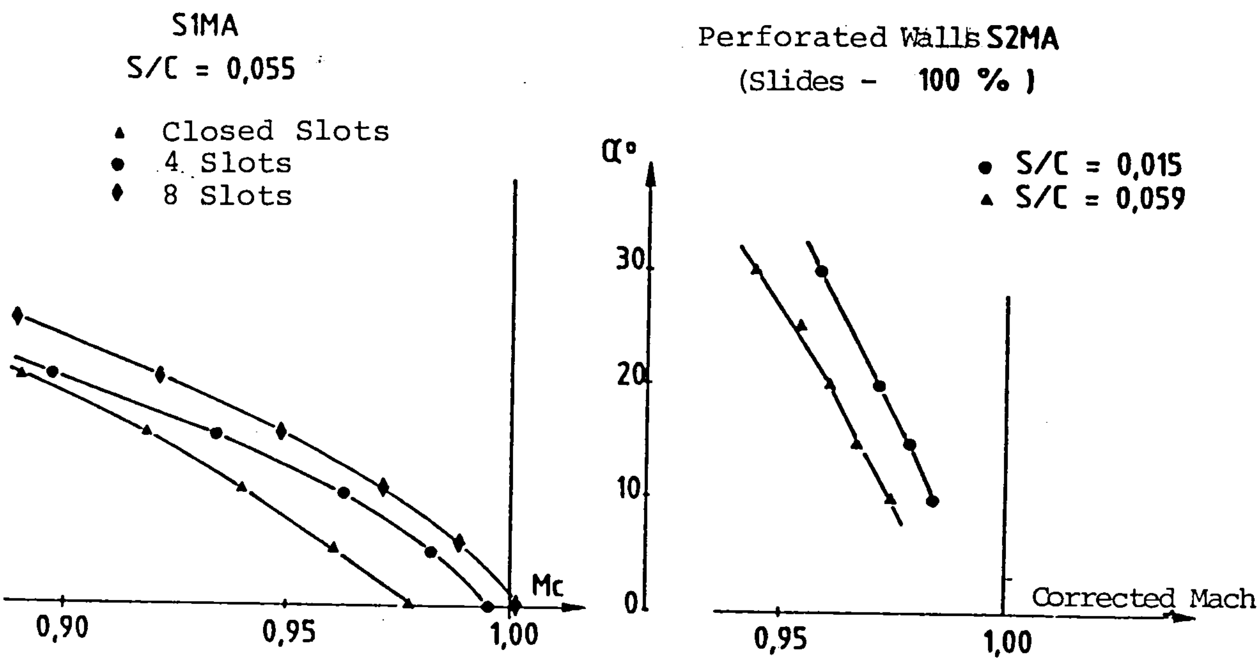



Fig. 13 - Limitations Due to Supersonic Field

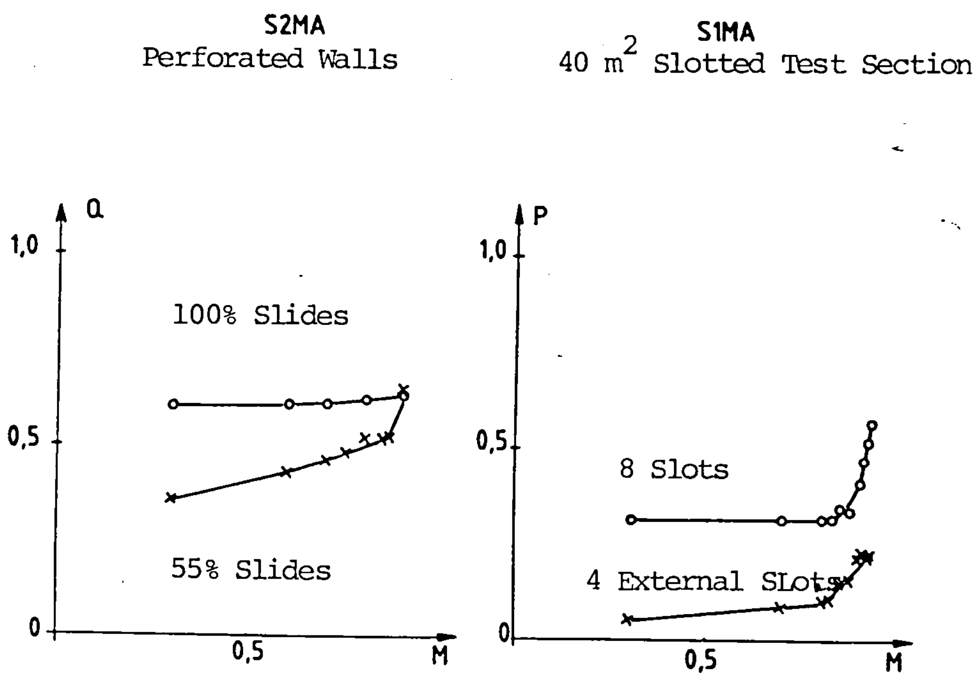



Fig. 14 - S1Ma, S2MA Porosity Laws

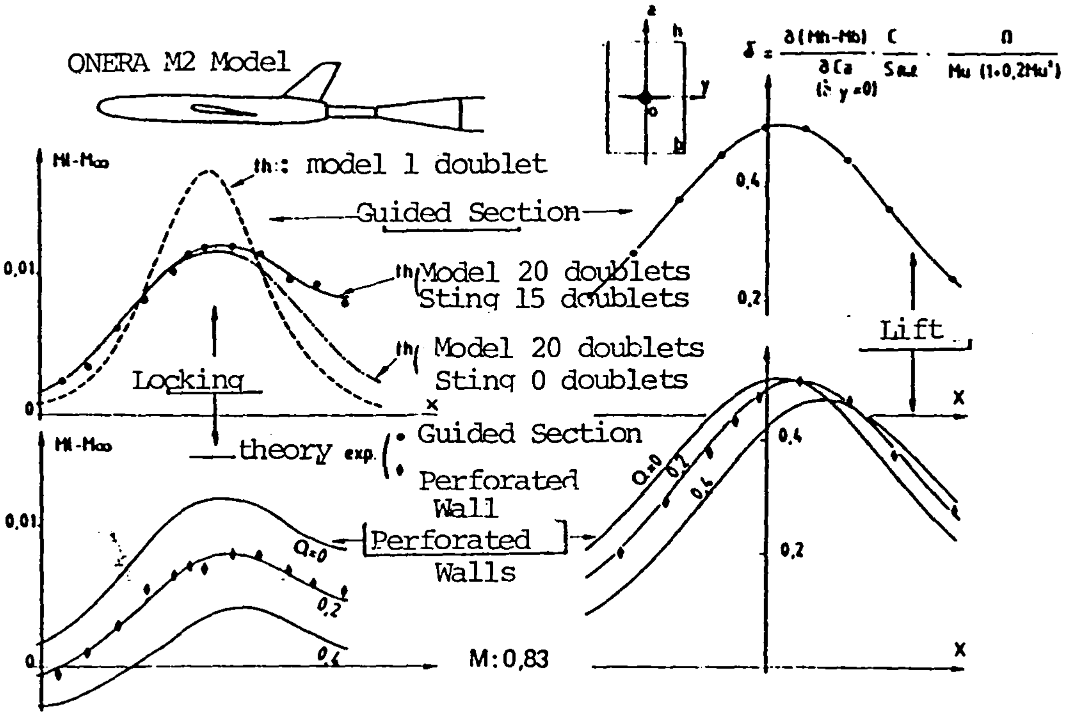



Fig. - Signatures on Perforated and Solid Walls - S3MA

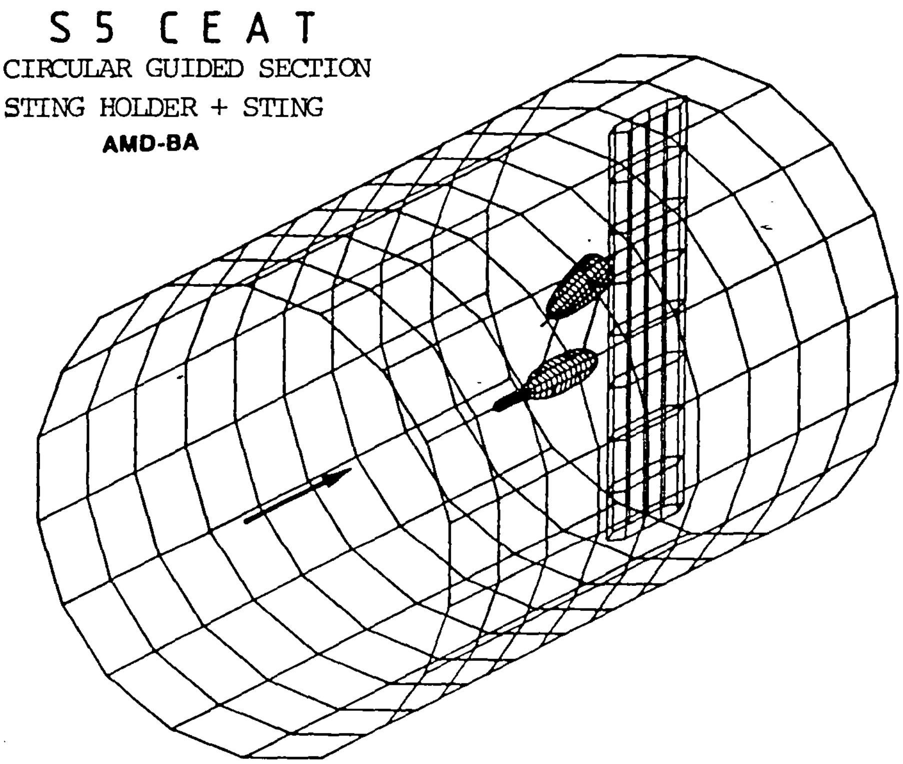



Fig. 16 - Sting Interference in Guided S5 CEAT Test Section

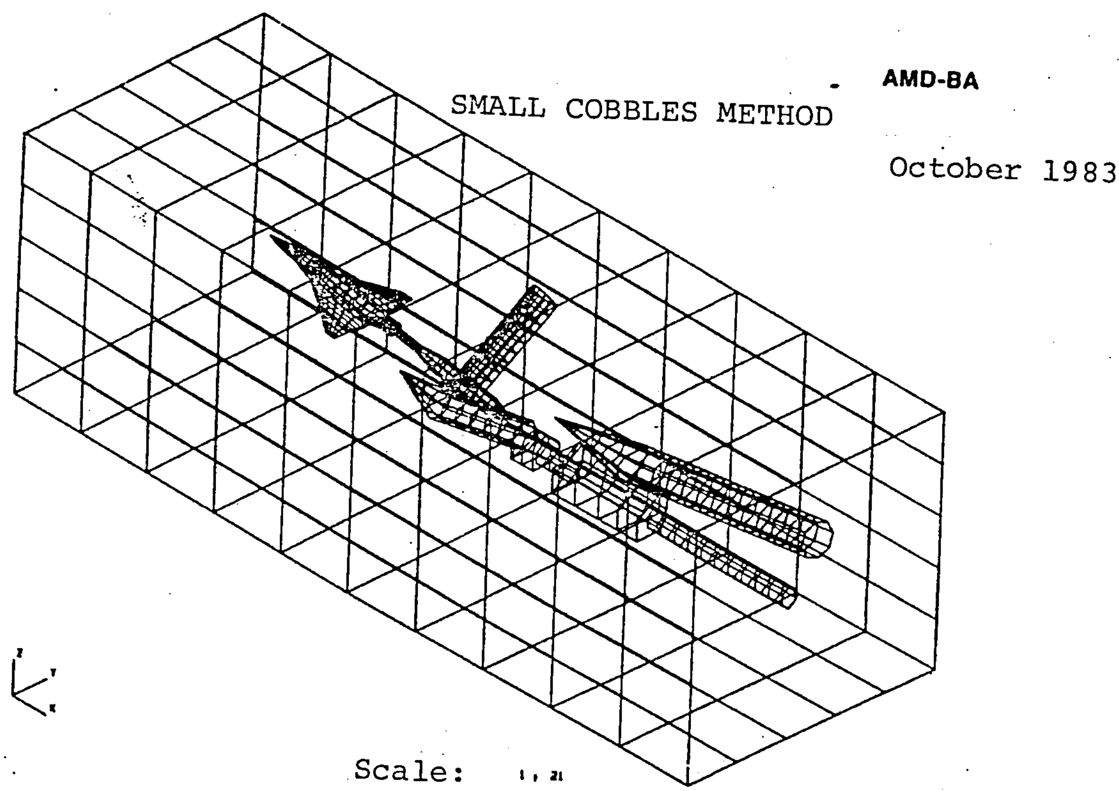
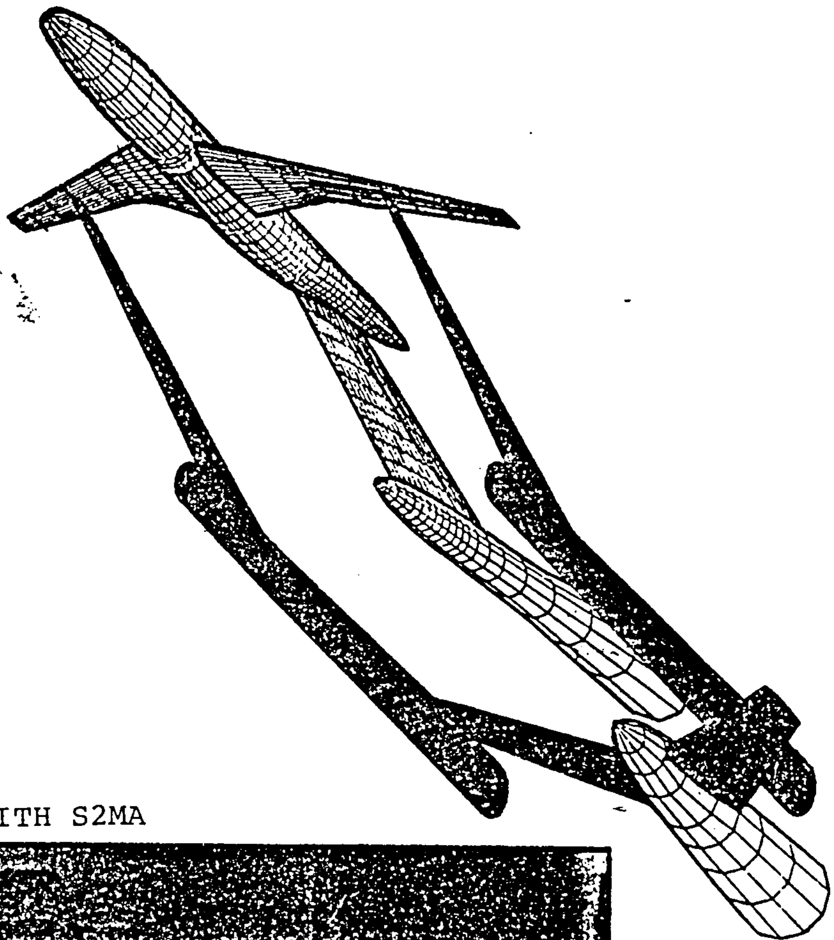
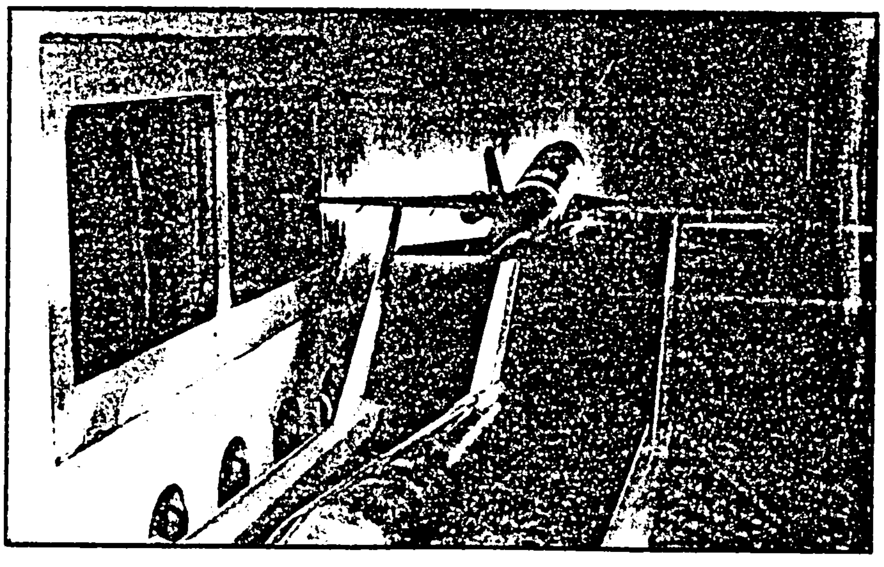



Fig. 17 - Support Interference in S2MA Guided Test Section



ASSEMBLY WITH S2MA



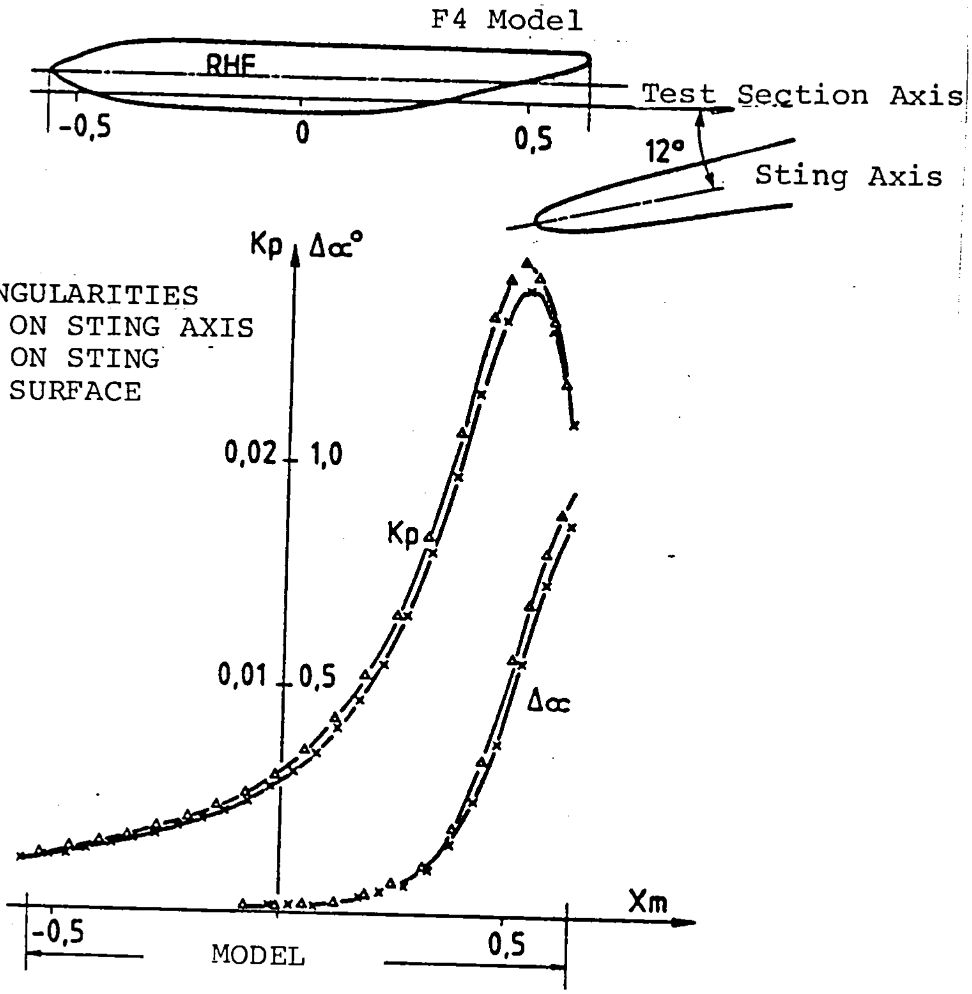
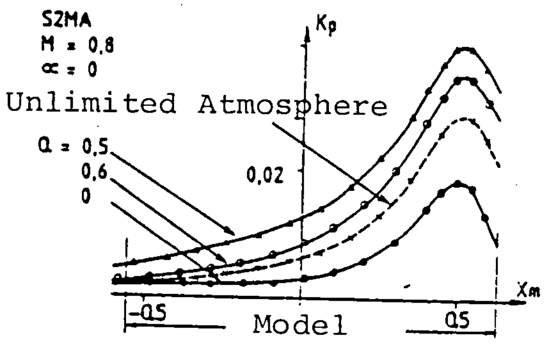



Fig. 19 - Sting Interference. Calculations in Unlimited Atmosphere.



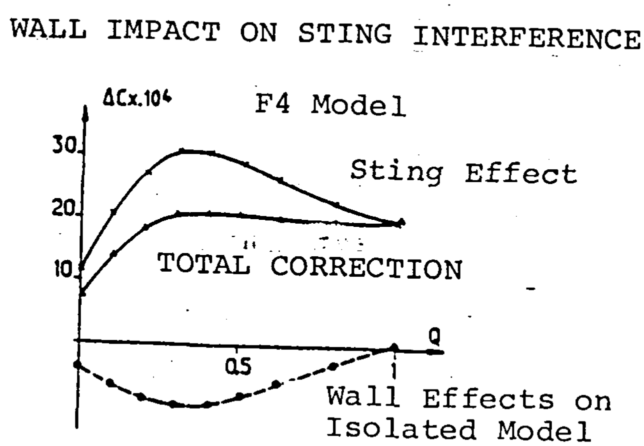
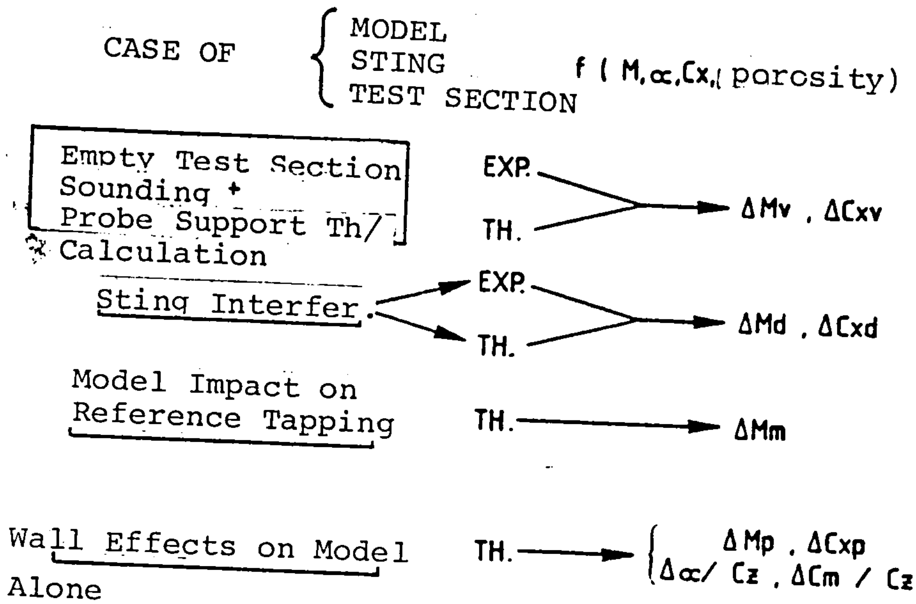



Fig. 20 - Wall Effects on Sting Interference




RESULTS/CORRECTION TABLES

Chart $\frac{\Delta\alpha_T}{Cz_c} = f\,(M, \alpha, Cx,$ porosity

or $$\frac{\Delta\alpha_T}{Cz_c} = \underbrace{\frac{qc}{qu}\left(\frac{\Delta\alpha}{Cz}\right)}_{\text{Lift}} + \underbrace{\left(\frac{qc}{qu} - 1\right)}_{\text{Lock}}\frac{1}{Cz_\alpha}$$

c = Corrected
u = Not Corrected

Fig. 21 - Preliminary Corrections Calculations

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WALL EFFECTS IN WIND TUNNELS

J.P.. Chevallier and X. Vaucheret

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**WALL EFFECTS IN WIND TUNNELS**

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O.N.E.R.A., Colloqium on ıce, November

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16. Abstract
A synthesis of current trends in the reduction and computation of wall effects is presented. Some of the points discussed include: (1) for the two-dimensional, transonic tests, various control techniques of boundary conditions are used with adaptive walls offering high precision in determining reference conditions and residual corrections. A reduction in the boundary layer effects of the lateral walls is obtained at T2; (2) for the three-dimensional tests, the methods for the reduction of wall effects are still seldom applied due to a lesser need and to their complexity: (3) the supports holding the model of the probes have to be taken into account in the estimation of ~~perturbatory~~ interference effects.

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WALL EFFECTS IN WIND TUNNELS

by J.P. Chevallier and X. Vaucheret

INTRODUCTION /3*

NTF

The recent first commercial operation of the NRF high Reynolds number wind tunnel (NASA Langley) [1] , the European ETW wind tunnel project [2] and the continuous request of manufacturers for more specific test conditions in existing installations have led to the creation of different work groups to study the problem of wall effects from the three-fold standpoint of their determination, their reduction and their correction. We may mention in particular an AGARD work group under the auspices of the "Wind Tunnel Testing Subcommittee of the Fluid Dynamics Panel" [3], and the GARTEUR action groups [4]. The most important results were also presented during the following meetings:

-AGARD-FDP Meeting at London on May 19, 20, 1982 (17 reports on wall effects in wind tunnels) [5];

-AGARD FMP Meeting at Smyrne on October 11 to 15, 1982 [6];

-Working sessions on "the reduction and correction of wind tunnel wall effects" NASA Langley Research Center January 25-26 1983 [7].

-53rd AGARD FDP Meeting on "Wind Tunnels and Testing Techniques" at Cesme on September 26 to 29, 1983 where 36 reports were presented, particularly that of Bignion and Kraft [8], presenting the conclusions of the 1982 meeting at London [5].

Of all studies presented, our purpose is to reveal which of these are current trends and to specify our own practices. To accomplish this, we shall first examine the means currently used to reduce wall effects, then recent methods of calculating these effects, because the two problems are now intricately interrelated.

It seems that there is a quasi general agreement on the need to use measurements of the velocity ~~speed~~ field in the vicinity of the walls to calculate interferences. Measurements of the same type will be used for testing the boundary conditions when we try to minimize these interferences.

In the second part the methods are applied to industrial wind tunnels based on wall ~~parietal~~ boundary measurements so as to test the representation of the model and its support.

boundary

1 - VARIOUS METHODS FOR REDUCING OR CALCULATING WALL EFFECTS

1.1 - REDUCING WALL EFFECTS

This reduction in wall effects ~~It~~ is generally achieved ~~because the term~~ using "adaptive walls" ~~is used.~~ This ~~It~~ is a vague term covering highly diverse practices using for example:

-permeable walls (perforated walls with variable porosity, segmented ~~fractionated~~ suction chambers, controlled back-pressure; changing slits with valves or counterplates; transvers~~al~~e flaps),

-flexible solid walls. /4

Various devices for measuring the velocity ~~speed~~ field are combined with these means of testing the transvers~~al~~e flow component: isolated probes, longitudinal tubes fitted with pressure taps, laser velocimetry, ~~parietal~~ wall taps. We will limit ourselves to a brief description of operational systems, the results of which are published and to the most advanced projects, primarily for two-dimensional testing. The characteristics reduced in terms of test section height (table 1) ~~facilitate~~ allow comparisons.

comparisions

-Wind Tunels With Perforated Walls and Multiple Chambers

The first developed at CALSPAN based on Sears' ideas [9] has a section 25 cm wide and 30 cm high, walls with normal perforations (22.5% opening) with 8 lower chambers and 10 upper chambers, tested individually. Measurements of the flow speed and direction on the control surface, performed at the beginning with clinometric probes now are due to the calibration of longitudinal tubes, equipped with 2 rows of pressure taps arranged perpendicular to one another ~~over opposite generators~~. These tubes, installed over a rotary support, should enable measurements to be performed on a cylindrical control surface for the extension of three-dimensional flows (Wind tunnels 1T, then 4T of AEDC) figure 1.

-Wind Tunnel With Slits and Multiple Chambers

At NASA Ames ~~the center of AMES~~ [10], a 25 x 13 $cm^2$ wind tunnel has 6 suction compartments for each wall. These compartments are in turn divided span ~~width~~wise into 3 chambers for a three-dimensional adaptation. The measurement of 2 disturbance speed components on one control surface is replaced by the use of 2 control surfaces with measurement of the one cross-component using a laser velocimeter.

-2D Wind Tunnels With Solid Flexible Walls

At the Univeristy of Southampton, the TSWT (Transonic Self Streamlining Wind Tunnel) has a 15 x 15 $cm^2$ square section and a very long test section (1.12 m) whose upper and lower walls are each shaped using 20 electric actuators with a similar number of wall ~~parietal~~ pressure taps [11]. As such the wind tunnel was used for two- and three-dimensional testing to determine whether the disturbances ~~to be~~ measured on the walls ~~of these~~ are difficult to obtain with precision (figure 1).

At the Technical University of Berlin [12], the T.U.B. wind tunnel has a 15 x 15 $cm^2$ square section with two flexible walls over 0.69 m each shaped by 8 direct current acutators with a 25 mm path and equipped with some 20 pressure taps.

At CERT at Toulouse, the T2 wind tunnel [18], which was the subject of 2 reports [13, 14] has over its competitors the advantages of one order of magnitude at least with respect to the Reynolds numbers (0.37 x 0.38 $m^2$ test section and generating pressure 5 bars ~~5b~~) and an excellent relative precision in the knowledge of wall shapes (using potentiometers of about 0.05 mm) accuracy and ~~speed~~ velocity distributions (with 91 pressure taps on each wall). By minimising ~~vectorizing~~ the program for calculating the virtual field and optimizing the relaxation factors reducing the time required for adaptation during a tunnel run ~~gust~~ of a few tens of seconds.

In addition to these advantages, the T2 wind tunnel has a relatively short test section (table 1). What can we conclude about the precision of the reference conditions obtained in these conditions? We shall return to this essential point after a brief review of the new methods of assessing wall effects. It should be pointed out that an attempt has been made to compensate for lateral boundary layer effects using reliefs made by gluing paper cut out in the shape of stream ~~level~~ lines [15]. This procedure finds its justification in recent CEAT tests [16] which show the existence at the root of the model of two small counter-rotating ~~ive~~ vortices, very different from the model ~~ization~~ representation proposed by Preston [17]. /5

3D Wind Tunnels With Flexible Walls

At the AFFDL ~~NASA center of~~ at Wright Field, a 9" x 9" test section (i.e. about 23 x 23 cm) is operating ~~under 4b~~ (figure 5) which has 2 flat side walls whereas the other two are made up of flexible rods with alternating circular and triangular sections activated by some 100 actuators. No measurements ~~was~~ were performed on the side walls [3].

At the Technical University of Berlin [12] a second test section, with an 18 x 15 cm$^2$ octogonal section, is used for 3D tests. The feasibility of such tests was ~~demonstrated~~ described recently in an ~~operation~~ presentation at Cesme in September 1983 (figure 3), despite the small wall deformations ~~to be achieved~~ required (of the order of one mm).

At DFVLR, in the advanced project, Dehnbare Adapative Mebstrecke (DAM) the circular test section was made up of an ~~elastic~~ rubber tube 800 mm thick whose diameter was stretched in~~to~~ 8 ~~sections by~~ directions by 64 ~~8~~ actuators [12] (figure ~~5~~ 4).

1.2 - NEW METHODS OF CORRECTING WALL EFFECTS

This was the title, in singular form, of a report presented at the 14th Symposium of Applied Aerodynamics at Toulouse in 1977 [19]. We still use this name for methods which have multiplied for 6 years and whose common points is to call on measurements made on ~~walls~~, or in the~~ir~~ vicinity of the wall boundaries. Created from the necessity of being applicable to adapt~~ive~~ed, but not perfectly adapted walls, this ~~type of~~ method has for conventional walls the advantage of eliminating certain controversial assumptions on linear~~y~~ boundary conditions [18, 20].

Without going into too much detail, we may mention the following methods in the order they appeared:

Kemp: the unknown intensit~~y~~ies of the singularities arranged at the walls and at the location of the model ~~is~~ are determined ~~to satisfy with~~ from ~~speed~~ velocity measurements ~~on~~ at an equal number of control points, on the model and at the walls, by resolving the linear system formed with the corresponding impact factors. The ~~parietal~~ boundary singularities thus defined contribute alone to the interferences under investigation.

-Smith [25]: the NLR I method differs from that of Kemp only in the limitation of the unknown singularities at the wall, the model being represented by given singularities, functions of its geometry and of overall lift and drag measurements.

Cap~~a~~elier et al~~ii~~ [19]: In contrast to the two aforementioned methods, ~~the~~ this formulation is expressed in terms of integrals of the ~~speed~~ velocity deviations measured at the walls and calculated for the model. This avoids resolving the linear system and therefore eliminates the consequences of random errors in the measurements. This method applies not only to the two-dimensional case, but also to three-dimensional flows in test sections with a rectangular section and flat side-walls.

Sawada [22] presented a very similar method which he recently applied to two-dimensional unsteady flows [37].

Mokry and Ohman [23]: Direchlet's problem of determining ~~for~~ the axial ~~speed~~ velocity inside the surface upon which boundary data are collected is solved in the form of a Fourier-Bessle series for three-dimensional cases. Their coefficients are obtained using rapid Fourier transforms.

For corrections calculated on the axis of the test section, a cylindrical control surface may be used no matter what the shape of the test section ~~has~~ is.

Mokry compared these methods [24] ~~on~~ for a two-dimensional test case and showed that [19] and [23] gave identical results and [22] and [25] deviated only very slightly.

Ashill [27] as well as Smith in the unpublished NLR II method avoiding the use of the model which may be delicate in the presence of supersonic or separation regions in the flow. They should therefore use measurements of the two disturbance components in the vicinity of the walls.

Mach=1

All of these methods are of the linear type and are limited for this reason below $M < 1$. Also they implicitly assume that the boundary conditions are homogeneous enough for the measurements near the walls to be significant.

For any method used, the precision required in knowing the two disturbance components will be brought to light through the explicit formulation of the ~~speed~~ velocity and incidence corrections, based on the relative longitudinal disturbance component $u$ [19] ~~cu~~, according to the so-called conjugated formulation [28], on the relative transversal component $v$. By letting $ui$ and $vi$ be the wall interference components at the center of the test section and by simplifying the formulas given in [18] based on an empty test section.

$$(1)\quad u_i(x,0) = \frac{1}{\beta h}\int_{-\infty}^{\infty} \frac{u(\xi, h/2) + u(\xi, -h/2)}{2\,\mathrm{Ch}\,\pi(\xi - x)/\beta h}\, d\xi$$

$$(2)\quad v_i(x,0) = \frac{1}{h}\int_{-\infty}^{\infty} \frac{u(\xi, h/2) - u(\xi, -h/2)}{e^{2\pi(\xi - x)/\beta h} + 1}\, d\xi + C$$

$$(3)\quad u_i(x,0) = \frac{1}{h}\int_{-\infty}^{\infty} \frac{v(\xi, h/2) - v(\xi, -h/2)}{e^{2\pi(\xi - x)/\beta h} + 1}\, d\xi + C'$$

$$(4)\quad v_i(x,0) = \frac{1}{\beta h}\int_{-\infty}^{\infty} \frac{v(\xi, h/2) + v(\xi, -h/2)}{2\,\mathrm{Ch}\,\pi(\xi - x)/\beta h}\, d\xi$$

No problem is raised by using formula (1) because it was shown that it tolerates the truncation of the integration, ~~terminals~~ owing to the rapid decrease in the impact function and the fact that it eliminates the reference errors. The same is true for formula (4) in regard to incidence. Conversely, for formula (2) it is necessary to determine the constant C. It is zero if we adopt as reference a flow direction which is sufficiently upstream so that the difference $u(\xi, h/2) - u(\xi, -h/2)$ is zero. It also shows in the nucleus of the integral a ~~speed~~ velocity difference which is delicate to measure.

Based on these formulas we therefore conclude that to apply the so-called new correction methods it is necessary to know, at a right angle with the model, the speed vector in modulus and direction, in the vicinity of the walls, with a precision of the same order ~~of~~ as that required for on so-called "upstream infinity" conditions.

## 1.3 - DETERMINING THE REFERENCE CONDITIONS

The crucial importance of determining these conditions accurately was recently recalled in a report under the "Wind Tunnel Testing Techniques" Committee of AGARD-FDP which set forth the requirements of airplane manufacturers with respect to wind tunnels [29].

The investigation of an error limited to $\Delta C_X = 0.0001$ leads to $\Delta M = 0.001$ and $\Delta\alpha = 0.01°$ in regard to the Mach number and the incidence. This goal, which seems a challenge, actually deserves considerable effort because in other sources [30] it is shown that a 1% gain in the cruise drag (considerable ~~only~~ in these oonditions) is profitable even if we have to ~~quintuple~~ quadruple the number of aerodynamic tests of a transport aircraft.

How can we possibly know the direction and speed of an "infinite upstream" flow in a wind tunnel with such accuracy?

Excluding the support effects, which will be discussed in the second part, and remembering that we have to know the direction and speed on a control surface with the same precision, by examining the errors inherent to the various procedures for measring the flow disturbance components (laser, clinometric probes, etc), here at ONERA we think that there is only one valid procedure: using deformable solid walls where the quality of the surface condition and pressure taps is equal to that obtained on airfoils and position measurements showing the shape of the wall (which will be corrected for the boundary layer displacement thicknesses).

Among the wind tunnels which try to achieve these conditions, we see that T2 has a shorter test section, but that it is long enough to define the reference conditions perfectly, given the balance functions discussed above. It has the largest number of boundary ~~parietal~~ pressure measurements and actuators near the model and the best definition of the wall positions. The range ~~scope~~ of the wall displacements is slightly smaller and as a result the dimension of the model is limited. The wall jack ~~displacement~~ pitch in other regions is too large ~~strong~~.

In these apparently optimum ~~optimal~~ conditions, has the objective under discussion ~~focussed on~~ been achieved? It is virtually impossible to calculate an error: the shapes of adaptive walls are derived by processing an external virtual flow using Green's formula and wall ~~whose~~ boundary velocity ~~parietal speed~~ measurements ~~are the data~~. Conversely, the flow accelerations normal to ~~over-speeds at a right angle with~~ the model are also functions ~~functionals~~ of /8
the slopes obtained by smoothing and interpolation of the measured dimensions. An intrinsic validation was therefore tried by placing the same model ~~mdoel~~ (CAST 7 airfoil with a 200 mm chord) on ~~over~~ the axis of the wind tunnel and at 80 mm below this axis. By adapting for each case, the wall shapes and wall ~~parietal~~ pressure distributions are totally different [15]. The variation of the lift factor as a function of the Mach number for angles of 0 and 1°, shown in figure 6 on a large scale, shows the scatter in ~~dispersion of~~ the measurements ~~measuring points~~. The data ~~latter~~ does not show any systematic deviation due to the difference in testing conditions and it seems small enough for us to be able to conclude that the objective is virtually if not fully achieved. This success in two-dimensional testing leaves promising prospects for extensions to three-dimensional flows provided that all precautions are taken to observe the purety of the flows, the homogeneity of the boundary conditions and the precision of the boundary ~~parietal~~ measurements in the presence of considerably smaller disturbance fields.

## 2 - WALL AND SUPPORT EFFECTS IN ONERA'S INDUSTRIAL WIND TUNNELS

In wind tunnels not yet equipped with adaptive walls and with magnetic suspensions, it is still necessary to make corrections for wall and support effects to restore as far as possible the results which would be obtained on models in an unlimited atmosphere. There are two types of corrections to be made for the potentials under consideration:

-the wall effects are calculated based on the interference potential ~~promoted~~ generated by the walls,

-the support effects are the result of the sum of the potential of the supports in an unlimited atmosphere and of the interference potential ~~promoted~~ generated by the walls.

### 2.1 WALL EFFECTS

Two methods are currently employed for calculating wall effects. These methods have already been presented.

The first method, called the "conventional method" [31] consists of calculating the potential ~~promoted~~ generated by the walls by solving a problem ~~whose data are the~~ which requires the following data:

-the potential of the model in an ~~unlimited atmosphere~~ unconfined flow unconfined flow,

-the boundary conditions on the walls of the test section involving the concept of "equivalent uniform wall porosity".

The second method, called the "signature method" [19] allows the potential ~~promoted~~ generated by the walls to be derived from data consisting of:

-the potential of the model in an ~~unlimited atmosphere~~ unconfined flow,

-the distributions of pressures measured on the control surfaces of the test section (signatures).

These two methods have in common the assumption of a cylindrical test section extending ~~reaching~~ to infinity, and the necessity of making use of a mathematical description of the model. /9

2.1.1 Mathematical Description of the Model

Since we are referring to a corrective calculation and not a calculation of the flow on the model, the specification of the model is rudimentary: it should include the required number of singularities for the model field to be properly represented at a distance from the model. The best way to control the specification consists of comparing the signatures measured and calculated on the walls of the test section in a configuration with perfectly known boundary conditions: in this case the use of solid walls is unambiguous.

The iterative process (figure 7) associated is as ~~the~~ followings: By the using signature measurements on the walls of a solid walled ~~guided~~ test section, in the presence and in the absence of a model, by adding and subtracting we find the components associated with blockages ~~parts for the locking~~ and lift ~~terms~~ corresponding to an isolated model. The model specification associated with zero porosity conditions of the walls makes it possible to obtain signatures at the same locations of the test section and to divide them into blockage ~~locking~~ and lift terms. An examination of the differences between calculated and measured signatures makes it possible to check whether the model specification should be improved and in this case which part of the specification, volume, wake, lift is to be altered to be acceptable in terms of manufacturer specifications.

Two examples illustrate the mathematical specifications of the model.

The first example concerns tests on a profile in a ~~flat~~ uniform uniform ~~current~~ stream in S3MA in a ~~guided~~ closed test section configuration. An example of the signatures measured in the presence of a profile, then corrected ~~of the~~ using readings in the absence of a profile (figure 8), show that the tapping errors were eliminated as well as the effect of the wake comb located downstream. A comparison of the calculated and measured signatures (figure 9) show that the lift distribution ~~description~~ due to two intens~~ity~~e vortices derived from measurements of $C_Z$ and $C_M$ is adequate [32]. At zero lift, the description of the volume using a single doublets is also adequate. Conversely, the description of the wake using a single source is increasingly incorrect when $Z_Z$ (therefore $C_X$) increases. This is due to the absence of ~~the tapping by considering the~~ separations in the model description. Work is now underway to correct this.

The second example concerns a space model (figure 10) in a 47 $m^2$ SIMA test section. The description of the streamlined bodies is here a number of double doublets based on ~~number of~~ the ratio between the length and diameter of the body. We see that the calculated signatures are in good agreement with the measurements, ~~personalize~~ representing well the shape of the model: the flat signature for the fuselage alone, and a more bulging shape for the entire spacecraft.

When the mathematical description of the model is considered to be correct, calculations may begin to correct the wall effects.

### 2.1.2 Signatures Method /10

As indicated above, this method does not require knowledge of wall porosities. One simply needs to measure the signatures over a control surface so that the wall porosity effects are homogeneous.

~~In~~ With perforated walls, and ~~a fortiori~~ solid ~~ones~~ walls, these control surfaces are the walls themselves. The ~~duration~~ extent of the signature measurements does not exceed that of the wake measurements of a

~~flat current~~ streamlined profile. This method is systematically applied to profile testing in S3MA. The corrected results obtained on the CAST 7 profile are in good agreement with those obtained in the test section with adaptive walls of the T2 wind tunnel of CERT/TOULOUSE (figure 11). ~~as well as for the lift curves and for the stability curves of the maximum $C_Z$~~.

In the case of walls with slits, the signatures may no longer be sampled on the walls. According to a recent publication [20], the signatures should be recorded at a distance from the walls which is virtually equal to the slit pitch. This is a problem for the test section which ~~as~~ has a limited number of slits.

2.1.3 ~~Conventional~~ Classical Method

In addition to a correction description of the model, it is necessary in the ~~conventional~~ classical method to know the wall porosity laws as a function of the Mach number and of the ~~generating~~ driving pressures and to validate the concept of uniform wall porosity.

The reference tests [31] ~~are referred~~ were made to determine the wall porosity laws. These tests may be ~~obtained~~ carried out by performing tests on the same model, ~~with~~ at the same Reynolds number:

-in the same test section rendered ~~guided~~ closed by ~~the~~ a ventilation mask,

-in a ~~test~~ test section with such dimensions that the wall effects are negligeable.

As far as possible the second type of reference choking is preferred because it has no limits due to the test section ~~locking~~ choking and does not require corrections which are high in three-dimensional cases.

The iterative process used for defining the porosity laws is the following (figure 12).

The work always includes an interpolation in M, $C_Z$ of the wind tunnel data. The first assessment of the deviations to be reabsorbed by corrections is established in incidence deviations as a function of $C_Z$ at a fixed Mach, and in $C_X$ deviations as a function of M for a given $C_Z$.

The deviations of M and $C_Z$ between interpolated results, corrected for the reference test and not corrected for the ventilated wall test are introduced into the curve networks established as a /11
function of porosity. This gives the first porosity law. It is used to correct the results of the ventilated wall test. The differences between the interpolated results corrected for both tests are then examined. If these differences satisfy the manufacturer's precision specifications, the work is completed. Otherwise, the process is repeated. In general, three iterations are necessary. If differences still exist, the reasons are investigated.

An examination of the pressure distributions measured on the walls of the test section make it possible to define the Mach-~~in-~~ incidence limits beyond which the Mach number is greater than 1. In fact, this value is obtained on the ceiling ~~and~~ when there is not yet complete chokings ~~any locking~~ choking of the test section: the supersonic region on the top surface ~~skin~~ of the wings reaches the ~~cieling~~ ceiling. The wall corrections are then no longer applicable. Figure 13 shows, for a corrected Mach number the limits obtained at SIMA for three ~~slit~~ slot conditions and at S2MA for 2 ~~homothetic~~ similar models.

In the case of an S2MA transonic test section, for two ~~used~~ conditions of the perforated walls (i.e. ~~by~~ opening slide valves by 100 and 55% to modify the porosity), the porosity laws (figure 14) were established by using as reference tests, tests on the same model in SIMA with an area 13 times larger than that of S2MA. These laws proved to be correct for full and half civilian aircraft models up to Mach 0.92 and for full military aircraft models up to the limits due to the growth of the supersonic zones.

In the case of a 20 $m^2$ SIMA test section, the porosity laws (figure 14) of 4-slotted or 8-slotted open configurations were defined in the reference for tests performed in closed slotted configuration. These laws are correct up to Mach 0.85.

Beyond this value, there are still differences between the corrected results, obtained for the three test section cases, and an attempt is being made to resolve these differences.

2.1.4 Indirect Signatures Method

One variant of the ~~conventional~~ classical method consists of basing ~~onself on~~ the ~~signatures~~ calculation ~~as~~ of the signatures on a function of the porosity parameter assumed to be uniform and by comparison with the measured signatures to derive the wall porosity cartography. This variant was used for the case of the S3MA perforated wall test section. After verifying the correct description of the ~~locking~~ blockage and lift terms in a ~~guided~~ closed test section, figure 15 shows that for perforated walls, a comparison of the signatures leads to a Q uniform porosity parameter Q of 0.2 on the walls. This porosity is moreover identical to that derived from the overall efforts in a ~~guided~~ closed reference test section.

In fact, this indirect signatures method is used to check the validity of the wall uniform porosity concept.

In test sections with perforated walls, a porosity test by comparing the measured and calculated signatures has not raised any special problems. ~~As~~ With this case, the concept of a uniform equivalent porosity was not handicapped by examining the signatures. The ~~conventional~~ classical method was retained because it is not penalizing in terms of computer time, after the porosity laws are established. Generally speaking, the more the porosity concept is uniform, the more the mathematical description of models and stings proves to be inadequate. /12

## 2.2 MODEL SUPPORT INTERFERENCES

Corrections of the Mach number and of the Archimed~~ean~~ian ~~thrust~~ buoyancy brought about by the presence of model supports may be obtained experimentally based on measurements of the Kp distributions at the location which the model fuselage axis would occupy. A clinometric ~~sounding~~ measurement would also make it possible to know the tail unit setting correction due ~~to~~ support~~s;~~ interference.

To avoid costly ~~soundings~~ measurements, a calculation may be performed. Two methods are used at present.

The surface singularities method begins with a meshing of obstacles ~~in~~ between the test section ~~of on its~~ walls. This technique is directly derived from techniques used by manufacturers in an unconfined flow ~~limited atmosphere~~ by adding the walls to simulate the ~~contained~~ confined in ~~atmosphere of~~ the test sections. Illustrations of the meshing are therefore borrowed from manufacturers. Figure 16 shows [33] the sting and sting holder in the S5 guided test section of CEAT-TOULOUSE used by DASSAULT-BREGUET. Figure 17 shows the meshing of a Mirage model installed on the wall of the S2MA closed ~~guided~~ test section and of the device with 6 degrees of ~~liberty~~ freedom to study load trajectories: calculations performed by LE BOXEZ of AMD-BA.

Figure 18 is concerned with the assembly of a civilian aircraft twin sting in a guided test section meshed by AEROSPATIALE. More complex cases including ventilated walls and descriptions of test section ends and upstream ~~parts~~ regions with tapered section are under study. This method is still complicated to use and requires powerful computers.

A description of test section obstacles using singularities distributed over their skeletons of various shapes has been tried recently by ONERA [34]. The only data required are the coordinates of the assmbly skeleton and the area rule.

An attempt is made to validate this method in an ~~unlimited~~ unconfined ~~atmosphere~~ flow by comparison with the results of previous more sophisticated methods. Figure 19 shows, in these conditions, a good agreement of the Kps and incidence promoted by an inclined support used in a sabre assembly of the F4 model.

The support description is tested in the ~~guided~~ closed test section by comparing the measured and calculated signatures. In this case, a description of the model-support system is used. Figure /13
14 shows the case of an ONERA standard model assembled ~~in~~ on a rendered closed straight sting in the S3MA ~~guided=rendered~~ closed test section. A model~~ization~~ representation with 20 doublets for the model and 15 for the sting provide a good agreement of the signatures.

Returning to the case of the F4 model in an S2MA transonic test section, figure 19 gives the Kp distributions on the line which the fuselage axis would occupy for various wall porosities.

We should insist on the relative magnitude of the wall effects and sting interferences. In the case of an S2MA wind tunnel (figure 20), in the perforated wall version with maximum ~~rate,~~ porosity the incidence corrections are zero. The drag corrections resulting from the longitudinal gradients promoted on the support sting and the wall effects are in a 3 to 4 ratio for a civilian aircraft model. The sting interference is more crucial for military aircraft models whose incidences may exceed 40 degrees (and even higher for missiles) [35,36]. Given these high values and the stresses to contain, the volumes of model support mechanisms are such that the wall effects for a well ~~conditioned~~ proportioned test section may seem secondary. This real problem, in the absence of a magnetic suspension, deserves to be considered first for future ~~active~~ adaptive wall wind tunnels.

## 2.3 APPLICATION TO INDUSTRIAL TESTING

We now have correct descriptions of models and its supports and of the test section porosity laws. As of now, the corrections are all calculated prior to testing for a specific test case ~~of a~~ defined by the test section, wall configuration, supports, and model.

These corrections (figure 21) include four parts:

-corrections relative to an empty test section obtained from corrected soundings measurements, if necessary, and from the influence of the probe support,

-calculated or measured support interferences,

-corrections ~~of~~ for wall effects and ~~of~~ the ~~field impact~~ influence of the model flowfield on the ~~test~~ reference tests.

In all the computer calculations provide a set of corrections depending on M, $C_X$, $C_Z$ (or incidence) expressed in the form of a table or polynomial laws which ~~are~~ can be introduced in the wind tunnel calculations to obtained real time corrected results. The correction calculations also provide the total ~~field promoted~~ flow field generated by the walls and supports, as well as ~~for~~ a Mach number distribution and incidence correction ~~on~~ at any point ~~of~~ on the model. It is easy to know the ~~spin~~ twist and camber corrections of the ~~wind promoted~~ flow generated by the walls and the local ~~M~~ Mach number and tail unit setting corrections due to the model supports.

## CONCLUSION

/14

The advantage of pressure measurements on the walls of test sections was has been clearly established for calculations of wall effects. For reasons of convenience, associated with the intended use of wind tunnels, these pressure measurements are ~~still~~ performed:

-occasionally in ~~3d~~ 3D to control the concept of uniform porosity of perforated walls and ~~to~~ to check the mathematical descriptions of models and supports in a ~~guided~~ closed test section,

-systematically in 2D for direct access to corrections,

-imperatively in test sections with adaptive walls,

-finally with care ~~suspicion~~ in test sections with slotted walls. The measurements should be performed at a distance from the walls which is physically ~~technologically~~ difficult to do.

If the advantage of additional measurements of the other component of the local flow on control surfaces is to eliminate any model description, a real problem of measurement precision has not yet been solved.

Optimized test configurations (test section, sting, model) is the result of a compromise between wind tunnel investments, the cost of testing and the quickness with which the results ~~prepared~~ are corrected ~~rectified~~. In three-dimensional cases, the wall effect levels are reduced by limitations in model size due to the span for civilian aircraft and ~~,~~ due to the length for high incidence military aircraft. Small displacements of flexible walls will require greater accuracy in pressure measurements and in the positions of wall ~~adaptive~~ actuators. Test sections with 3D ~~3d~~ adaptive walls are still too recent to know their application limits and operating difficulties.

Meanwhile, it is suggested to use adaptations to the ~~main~~ important ~~point~~ part of a test program. These adaptations may concern:

-models whose manufacturing specifications account for distorsions in the flow of conventional walls (as practiced for aeroelasticity);

-walls which should meet specifications using conventional padding whether or not associated with improved ventilation distributions.

In any case, continuous revisions of concepts for minimizing wall effects should follow improvements in the specifications for precision required by manufacturers.

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Table 1

Wind Tunnels With Controlled 2D Boundary Conditions

| Wind Tunnel | Location | Test Section Section: (L.H) | Test Section Length/H | Boundary Conditions Control Nb Points | Boundary Conditions (paths, Threshold/H | Model C/H |
|---|---|---|---|---|---|---|
| T.S.W.T. | University of South-Hampton | $15x15cm^2$ | 7.33 | 20 actuators | | 0.66 to 1 |
| T.U.B. | Technical University of Berlin | $15x15cm^2$ | 4.6 | 8 actuators | $\pm 0.16$ $5.10^{-4}$ | 0.66 |
| $T_2$ | ONERA-CERT Toulouse | $39x37\ cm^2$ | 3.5 | 16 actuators | 0.07 $10^{-4}$ | 0.3 to 0.5 |
| CALSPAN AEDC | Buffalo Tullahoma | $25x30cm^2$ | 4.6 | 10 boxes (perforated walls) | Longitudinal Tubes 0.3° | 0.3 to 0.5 |
| NASA Ames | California | $25x13cm^2$ | 5.66 | 3x6 boxes (slotted holes) | Laser Velocimetry over two 0.05° planes | 0.6 |

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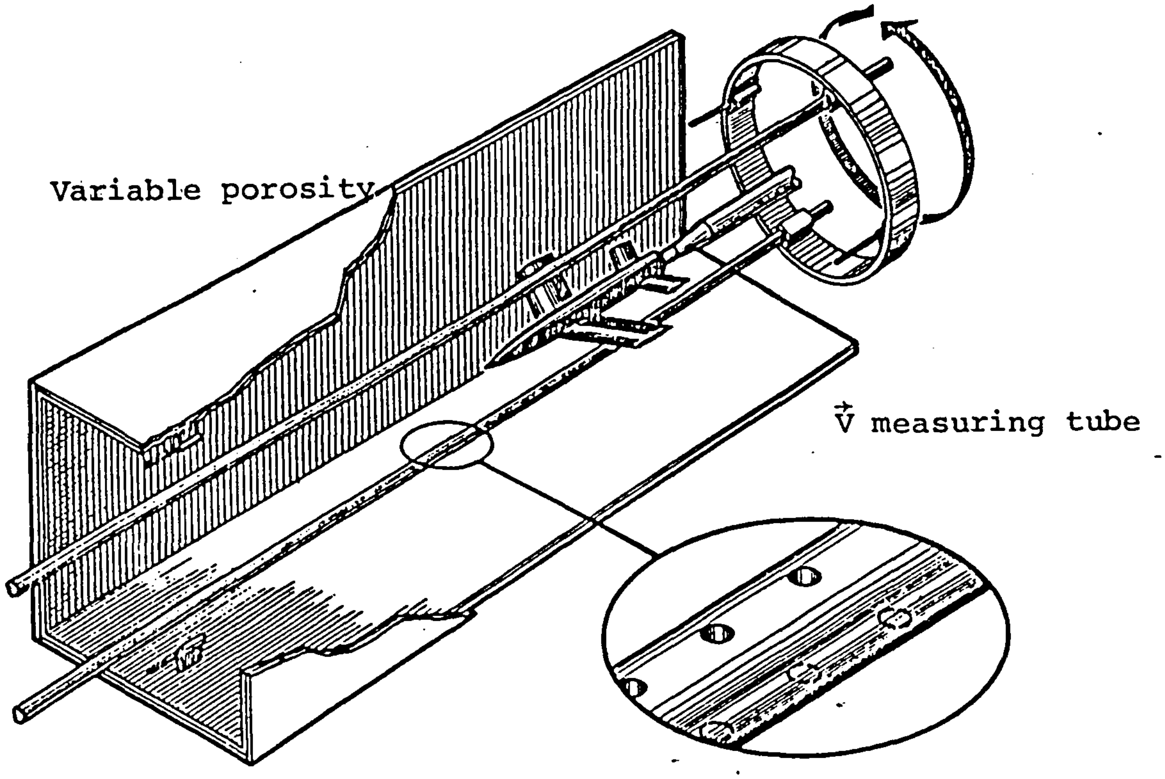


*Fig. 1 – A.E.D.C.* 1T TUNNEL

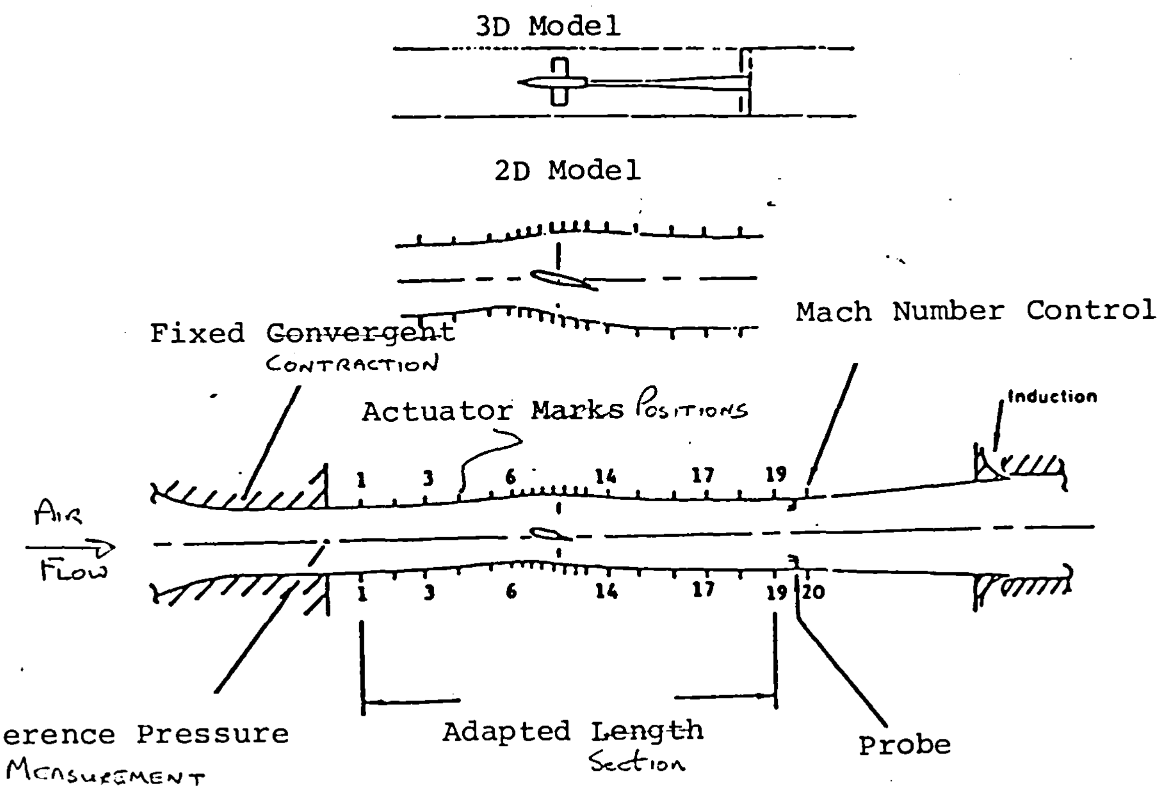


Fig. 2 - ~~Wind Tunnel of~~ TSWT at Southampton University, UK.

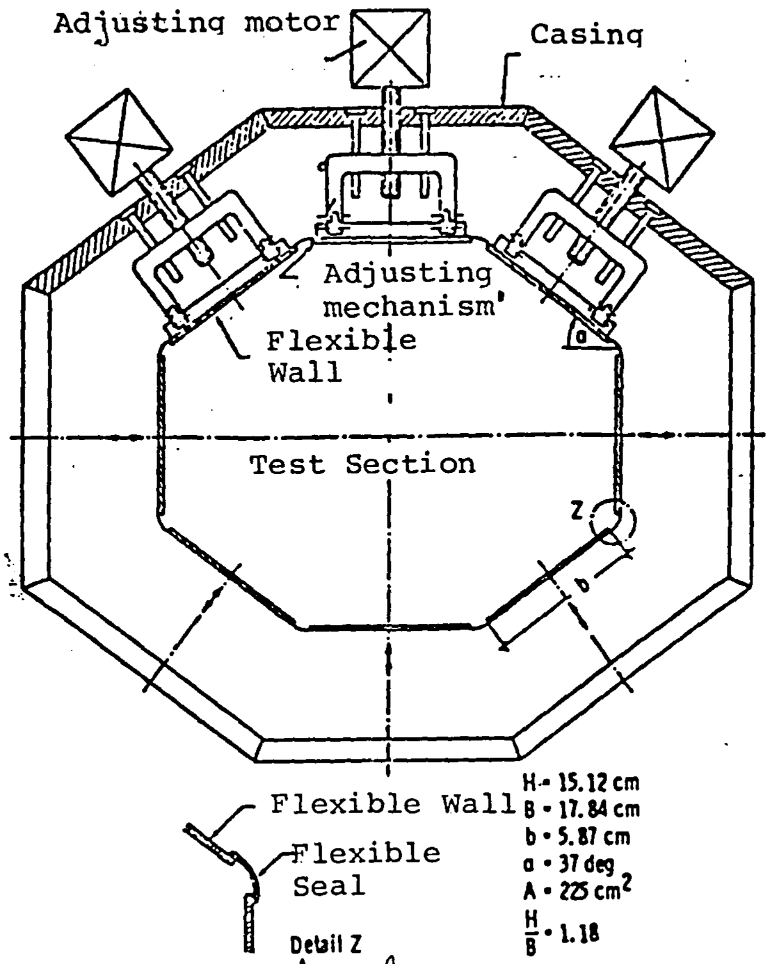


Fig. 3 - Technical University of Berlin Wind Tunnel

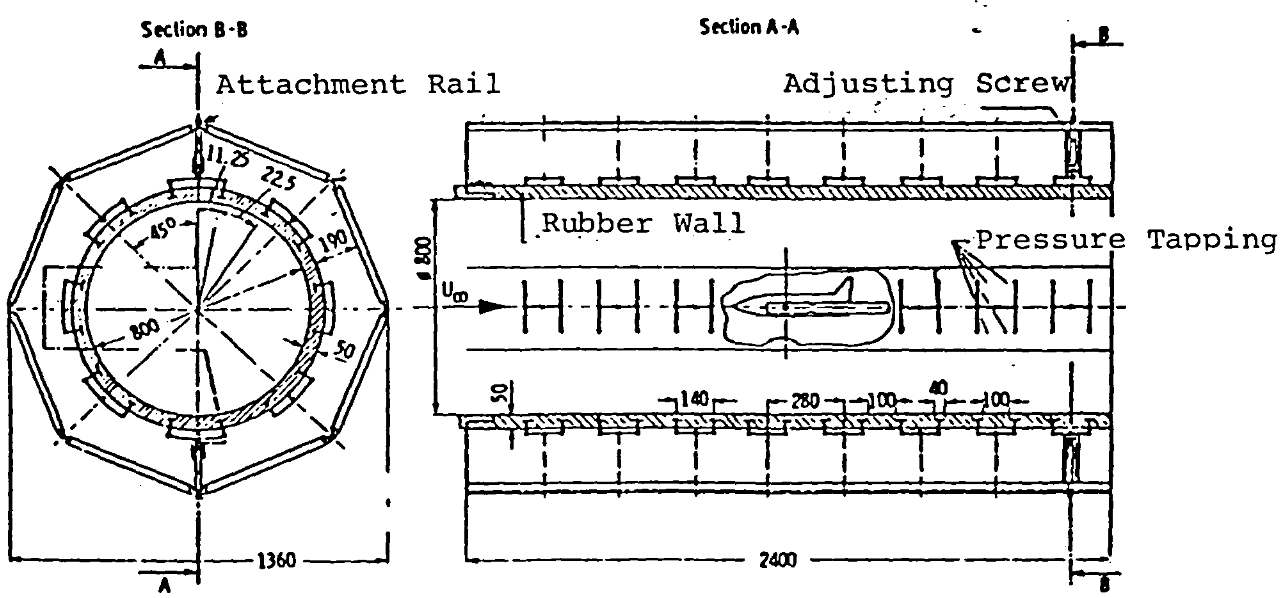


Fig. 4 - DFVLR Test Section Project with ~~Elastic~~ rubber Walls

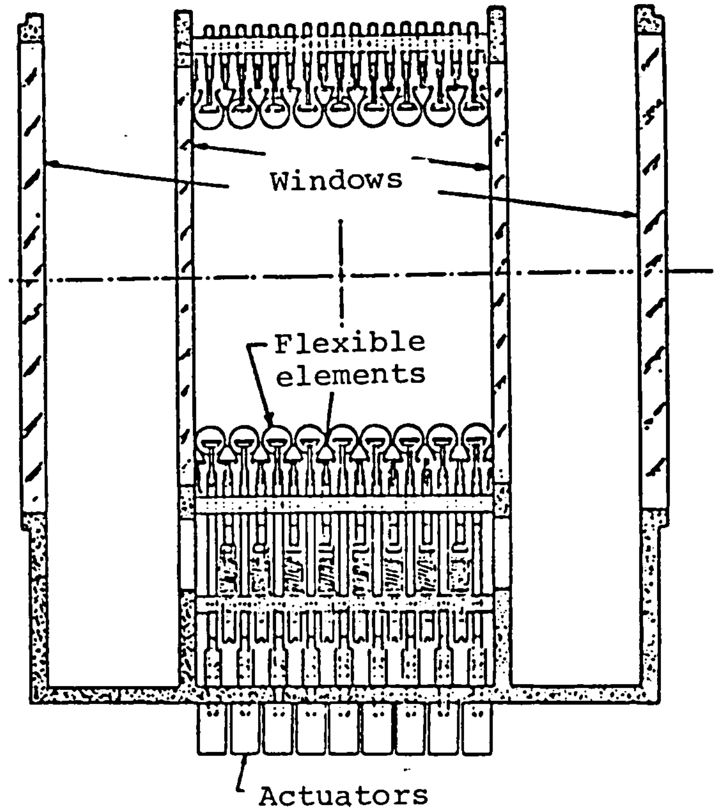


Fig. 5 - AFFDL Pilot Wind Tunnel With Flexible Wall Elements(Rods)

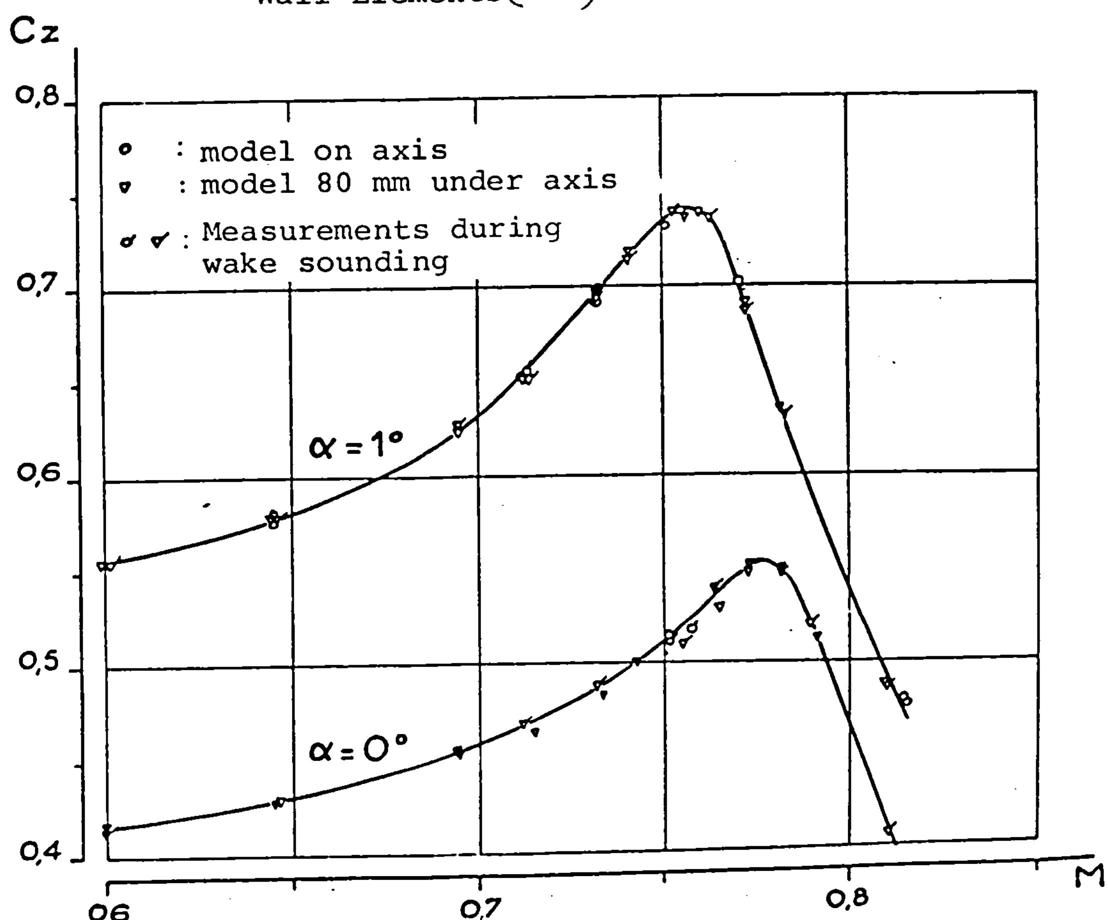


Fig. 6 - CAST 7 Profile. Lift as a Function of Mach Number

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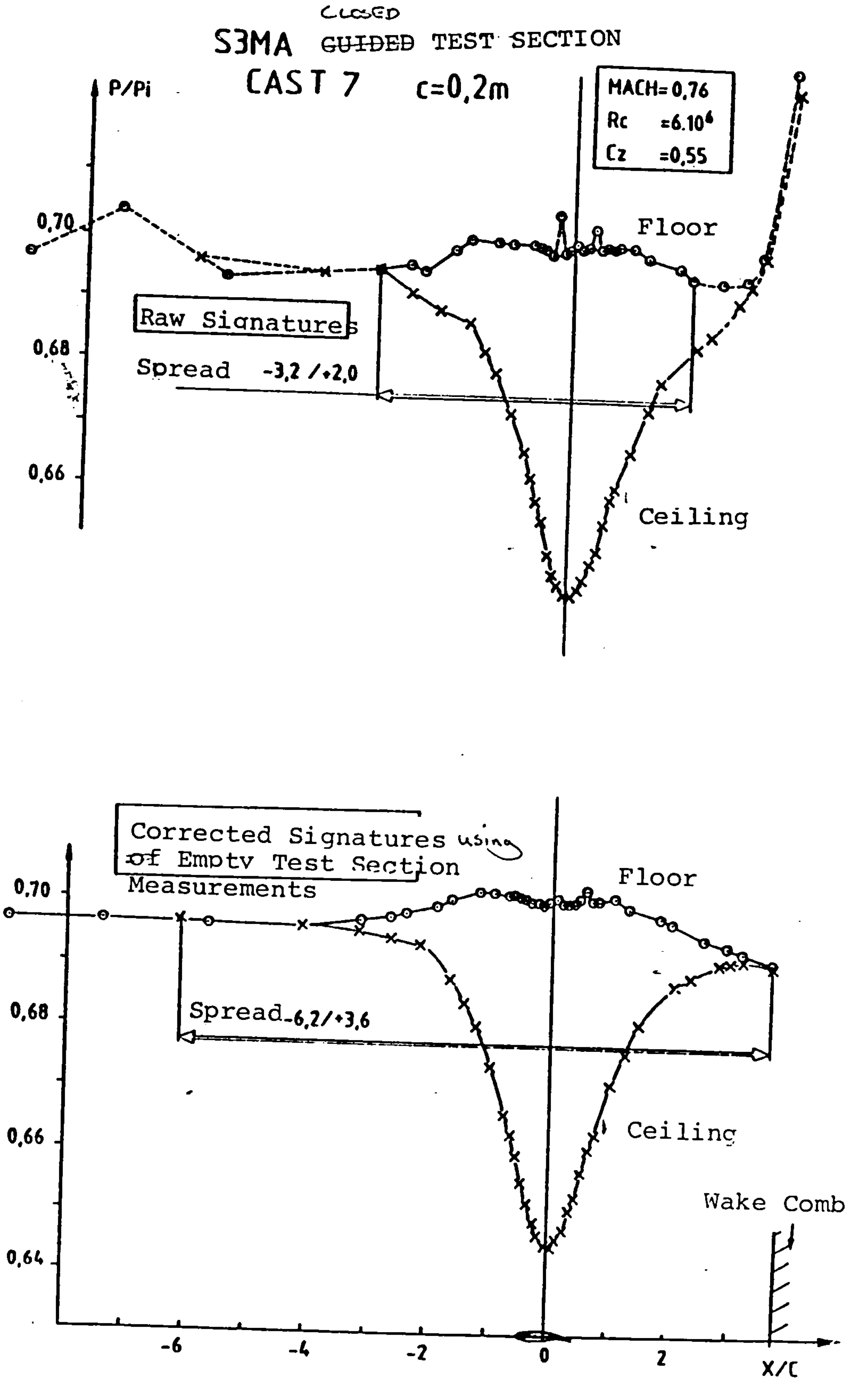


Fig. 8 - 2D - Rough and Corrected Signatures ~~of Empty Test Section~~

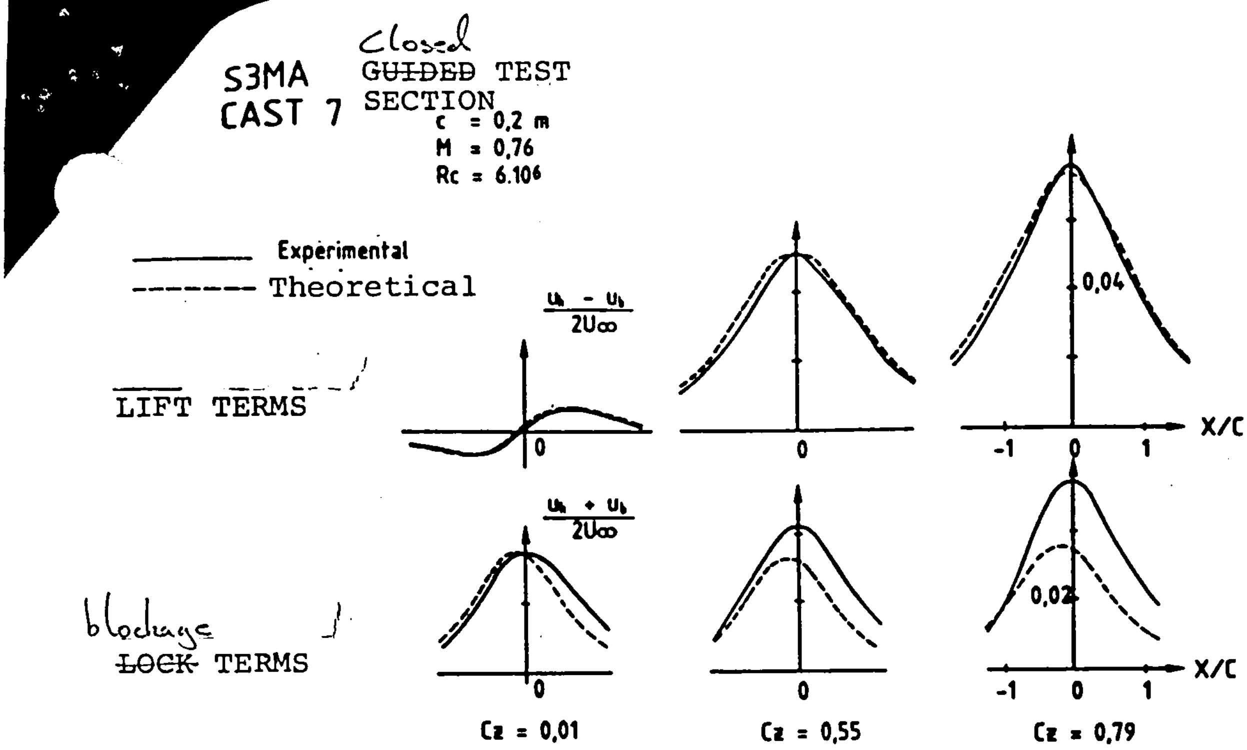


Fig. 9 - 2D Comparison of Calculated and Measured Signatures

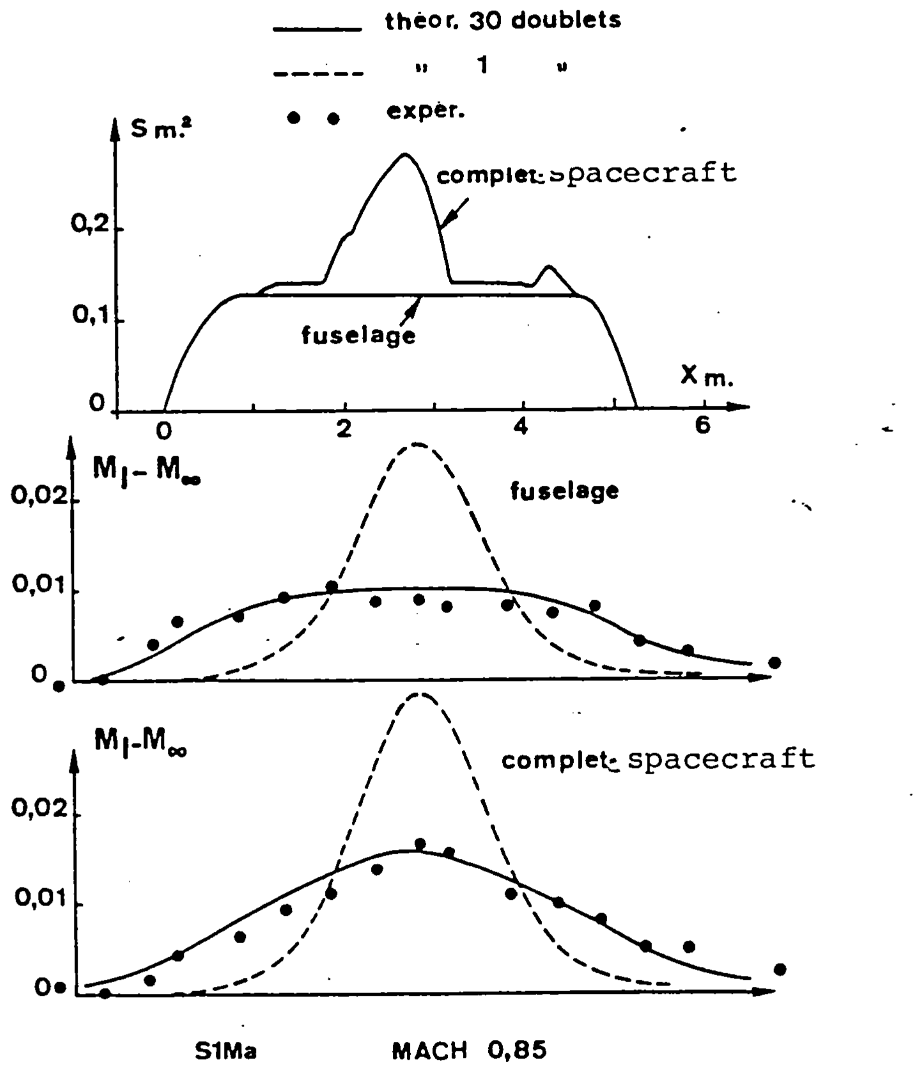


Fig. 10 - 3D Signatures on Solid Walls

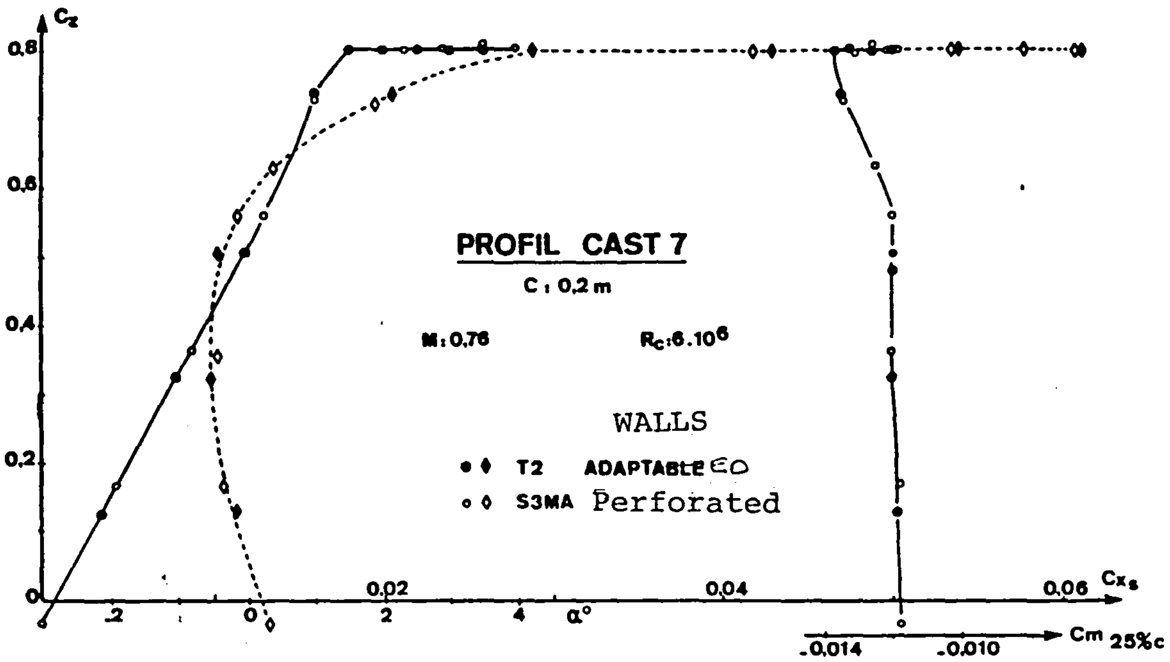


Fig. 11 - CAST 7 Profile - Comparison S3MA-T2 Results

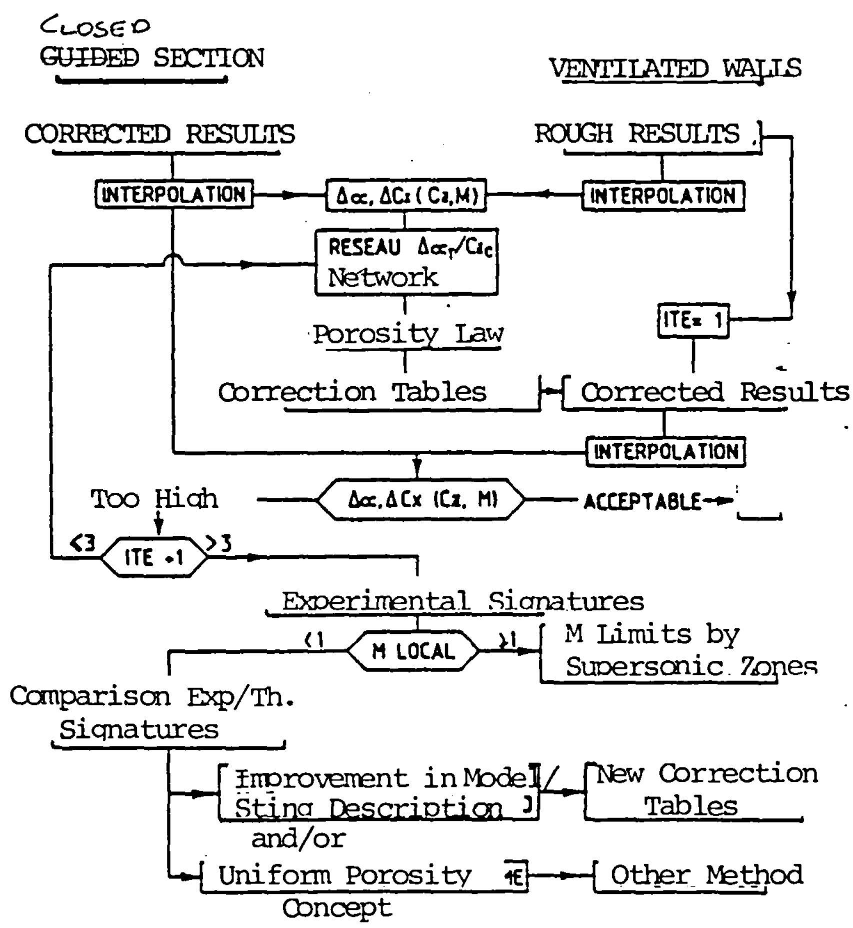


Fig. 12 - Determination of the Porosity Laws of a Test Section With Ventilated Walls.